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HYDRODYNAMICS IN DEEP AQUIFERS OF THE ILLINOIS BASIN

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ABSTRACT

Data on water levels, pressures, and water densities in deep aquifers in and around the Illinois Basin were collected. In the northern third of Illinois water appears to flow from the west to the east. In the southern half of the state water appears to flow southward, but the evidence for such flow is of doubtful quality. In the north central part of the state the indicated directions of flow vary in a random fashion.

The density of the water in these aquifers varies with depth and with location. Flow in such systems is quite complex; for example, differences in head can exist at the same elevation inside and outside a dome, even though no flow occurs. When flow does take place, it occurs principally along the roof of the aquifer. Some net head is available to cause vertical flow from the Mt. Simon Aquifer to higher aquifers; prior to modern pumpage this head probably was small.

Some conclusions are presented concerning the effects of variations in water density in problems related to gas storage, oil accumulation, origin of brines, and underground waste disposal; for example, a tilted oil-water interface can be maintained with zero flow.

INTRODUCTION

Data on equilibrium water levels and hydrodynamic potentials in aquifers are of interest to many people. Petroleum reservoir engineers and geologists are concerned with the possibilities for the existence of "tilted water tables" under oil and gas accumulations. Researchers who study the primary accumulation of oil need to know something about the direction and rate of flow of water underground. Others, interested in theories about the source of natural brines, need information about the natural forces available for forcing water through semiper-

meable membranes, such as layers of shale. Gas-storage engineers need to know whether hydrodynamic gradients exist that will add to, or subtract from, the effective closure in proposed storage reservoirs. Hydrologists are interested in the natural potentials that may cause flow in fresh-water sources or in other aquifers.

The present study was concerned with flow in deep aquifers in and around the Illinois Basin. Data on water levels and pressures in the aquifers, as well as on densities of the interstitial waters, were collected. For reasons to be given later, the head in terms of fresh water, $H^{1.00}$, was used, rather than the hydrodynamic potential, in efforts to interpret the results and to determine what flow, if any, occurred in and between the aquifers.

With respect to flow, the study area can be considered in three parts. In the northern third of Illinois water appears to flow from the west to the east. In the southern half of the state water appears to flow southward, but the evidence for such flow is of doubtful quality. In the north central part of the state the indicated directions of flow vary in a random fashion.

The density of the water in these aquifers varies with depth and with location. Flow in such systems is quite complex, as shown by a listing of some of the parameters that influence flow. A possible explanation of the indicated random flow in the northern part of the basin is presented.

Finally, consideration of the effects of variations in water density in aquifers leads to some important conclusions about problems related to gas storage, oil accumulation, origin of brines, and underground waste disposal.

Acknowledgments

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Nomenclature and Definitions

$H_{obs.}$ = observed head, with respect to sea level, feet

$H^{1.00}$ = head in terms of fresh water, with respect to sea level, feet

$L_{obs.}$ = length of observed water column, feet

$L_{eq.}$ = length of equivalent fresh-water column, feet

ρ = density of interstitial water, relative to fresh water

$\rho_{est.}$ = relative density estimated from plot of ρ versus total dissolved solids in water

Z = elevation with respect to sea level, feet

ΔZ_C = thickness of cap rock, feet

$\psi_\rho = [\Delta H^{1.00} - \int_{P_2}^{P_1} (\rho - 1)\, dZ]$ where $\Delta H^{1.00} = (H_2^{1.00} - H_1^{1.00})$. $H_1^{1.00}$ and $H_2^{1.00}$ are the values of $H^{1.00}$ at points P_1 and P_2, respectively. $\int_{P_2}^{P_1} (\rho - 1)\, dZ$ is the integral along a flow path from P_2 to P_1.

$\psi_{\rho_i} = \Delta H^{1.00} - (\rho_i - 1.00)\, \Delta Z$; ρ_i = value of ρ at point P_i in the aquifer

$\psi_{\rho_{ave.}} = \Delta H^{1.00} - (\rho_{ave.} - 1.00)\, \Delta Z$; $\rho_{ave.} = (\rho_1 + \rho_2)/2$

$\Delta Z = Z_1 - Z_2$, where Z_1 and Z_2 are values of Z at points P_1 and P_2, respectively.

s = distance between points P_1 and P_2, miles

DST = drill-stem test

ICIP = initial closed-in pressure, psig

FCIP = final closed-in pressure, psig

t = flow period, minutes

θ = shut-in time, minutes

ϕ = potential, feet, relative to sea level

S. L. = sea level

Summary of Previous Conclusions About Flow in Aquifers That Contain Water of Variable Density*

M. K. Hubbert's classical papers on the flow of ground water were published in 1940 and 1953. Since then many people have applied Hubbert's concepts to a variety of problems, including entrapment of oil, underground storage of gas, and flow of ground water.

Although Hubbert's original ideas have been extended into many areas of investigation, one important problem still needs some study and clarification: the problem of determining the direction and rate of flow of underground waters whose density varies from point to point because of changes in the concentrations of dissolved solids.

McNeal (1965) touches upon this problem. In a personal communication (1969), he gives a procedure for correcting potentiometric surface maps in basins where water density varies; a pressure correction, ΔP_s, is subtracted from recorded pressures, where

$$\Delta P_s = \Sigma\ 0.433\,(\rho_{sw} - \rho_{fw})\,\Delta Z,$$

and ρ_{sw} and ρ_{fw} are specific gravities of salt water and fresh water, respectively, and ΔZ is the vertical distance over which each type of water exists.

Hitchon (1969a) says, "Flow in variable density water systems, such as exist in most sedimentary basins, may be empirically represented by using a standard density." He describes a method that involves dividing an area into discrete density regions. Using a best-value density, hydraulic-head maps are made for each region and flow lines are constructed within each region. If there is no opposed flow between any two regions of differing densities, it may be concluded that the flow paths can be empirically represented by using a standard density throughout the system (Hitchon, 1969b).

Hanshaw and Hill (1969) say, "One can attempt to correct all the potentiometric data for salinity variations, but this is a difficult task. Not only must one correct for the density of water in the aquifer at the well site, but one must also consider the integrated density of all water in that aquifer which is at higher points on the potentiometric surface."

These authors do not give the basis for their statements about density corrections. The derivation of their pressure corrections needs to be outlined. Terms such as "integrated density" need to be defined, and the implications of density effects with respect to possibilities for flow need to be clarified.

Hubbert (1953, p. 1995) discusses the problem briefly. In particular, he shows how to handle the case of a basin in which the salinity of the water increases with depth. Pressure and density measurements are taken in a row of wells extending down dip from the flank of the basin. A well in the middle of the row is used as a reference well; the density of the water in this well is used as a reference density. At each of the wells, the potential of the water having the reference density is calculated, using this density and the pressure measured in the well. The plot of potential versus distance shows whether the water is static (minimum in curve) or flowing (direction of flow is tangent to curve).

This treatment appears to be valid for the idealized case in which the basin is assumed to consist of a set of perfect saucers, with no sharp changes in

*This review is taken partly from "Pressure Observations and Water Densities in Aquifers and Their Relation to Problems in Gas Storage" by D. C. Bond and Keros Cartwright, 1970, Journal of Petroleum Technology, v. XXII, p. 1492-1498. Material from that article used in this circular is printed with the permission of the Journal of Petroleum Technology.

salinity with distance and no barriers to impede flow. It may have limited application to a real basin. It has been shown that a trough containing dense water can serve as a barrier to flow. In an area where salinity is changing rapidly, where waters are stratified, and where structural troughs exist, Hubbert's method may not apply (Bond and Cartwright, 1970).

Lusczynski (1961) studied systems in which fresh water and sea water moved through an aquifer under the influence of gravity near sea level. He defined "point-water head" at a point as the water level, referred to sea level, in a well filled with enough water of the type that exists at the point to balance the existing pressure at the point. For such systems "point-water head" is equivalent to Hubbert's "potential." Lusczynski introduced the concept of "environmental-water head," which he defined thus: "Environmental-water head at a given point in ground water of variable density is defined as a fresh-water head reduced by an amount corresponding to the difference of salt mass in fresh water and that in the environmental water between that point and the top of the zone of saturation." He used a quantity, ρ_a, which is the average density of water between sea level and the point of investigation. Equations were deduced involving point-water head, environmental-water head, and ρ_a; these equations appear to be useful in deducing information about direction and rate of flow (Lusczynski, 1961, p. 4249-4250).

Lusczynski's conclusions appear to be valid and useful for the relatively simple systems that he studied. In deep, high-pressure aquifers his conclusions will be difficult to apply. In such aquifers it may be difficult, if not impossible, to determine accurately the density of the interstitial water at one point, let alone at a series of points at various levels in a well. Lusczynski's method appears to be valid only when the aquifer extends from the surface downward to the zone of investigation; in general, deep, high-pressure aquifers are isolated from the surface by impermeable rocks. Also, as shown by Bond and Cartwright (1970), troughs and "corrugations" in flow paths in variable-density systems can influence flow greatly. Only in rare cases will the geometry of the possible flow paths and the density of the water be known in enough detail to permit a treatment like that of Lusczynski.

Flow through aquifers containing water of variable density was studied by Bond and Cartwright (1970). In order to avoid ambiguity about the implications of potential in such systems, they used hydrostatic head rather than potential. Following are some of their conclusions:

1. In an aquifer containing water whose density varies from point to point because of changes in the concentrations of dissolved solids, knowledge of the hydrostatic head at two points does not necessarily enable one to determine the direction of flow, if any, between the two points.
2. In general, no flow occurs along a given flow path if

$$\Delta H^{1.00} = \int_{P_2}^{P_1} (\rho - 1.00)\, dZ.$$

   A trough filled with dense water can serve as a barrier to flow.

3. Where waters are stratified in an aquifer according to their density, the "potential" of a well has no unique value; instead, the potential (or the head) at a point in the well or in the aquifer should be considered. In such a variable-density aquifer, differences in observed head do not necessarily indicate flow through the aquifer, even though the produced waters from different wells in the aquifer have similar densities.
4. Water flows upward through conduits in a cap rock if

$$(H_2^{1.00} - H_1^{1.00}) > (\rho_2 - 1.00)\Delta Z_c.$$

Water flows downward if

$$(H_2^{1.00} - H_1^{1.00}) < (\rho_1 - 1.00)\Delta Z_c.$$

No flow occurs (static interface exists between the two waters within the cap rock) when

$$(\rho_1 - 1)\Delta Z_c < (H_2^{1.00} - H_1^{1.00}) < (\rho_2 - 1)\Delta Z_c.$$

That is, the interface acts like a valve which prevents flow through any conduit that may exist in the cap rock. The distance, $\Delta Z_{eq.}$, from the bottom of the cap rock to the equilibrium interface is given by

$$\Delta Z_{eq.} = [H_2^{1.00} - H_1^{1.00} - (\rho_1 - 1.00)\Delta Z_c]/(\rho_2 - \rho_1).$$

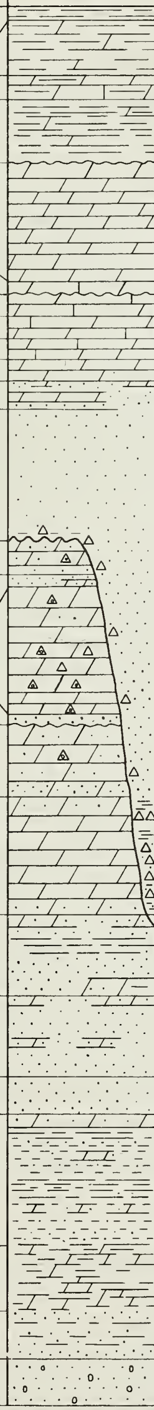
(Here $H_1^{1.00}$ and $H_2^{1.00}$ are the values of $H^{1.00}$ at the top and the bottom of the cap rock, respectively; ρ_1 and ρ_2 are the relative densities of the waters in the aquifers above and below the cap rock, respectively, and ΔZ_c is the thickness of the cap rock.)

HYDRODYNAMICS IN DEEP AQUIFERS OF THE ILLINOIS BASIN

The present report summarizes the available pertinent information on water levels, water densities, reservoir pressures, and hydrodynamic potentials in the deeper rock strata (St. Peter Sandstone and deeper, fig. 1), in Illinois and parts of Indiana, Michigan, and Iowa. Information from these sources was used:

1. Drill-stem tests in drill holes (oil and gas tests, gas-storage wells, waste-disposal wells);
2. Equilibrium reservoir pressures measured in wells;
3. Virgin equilibrium water levels in wells, principally in gas-storage reservoirs.

This material was obtained from the files of the Illinois State Geological Survey and from individuals and companies listed in the acknowledgments. Much valuable information was also taken from testimony and exhibits filed with the Illinois Commerce Commission in hearings concerning proposed underground gas-storage projects.



SYSTEM	SERIES	STAGE	MEGA-GROUP	GROUP	FORMATION	THICKNESS (FEET)	LITHOLOGY
ORDOVICIAN	CINCINNATIAN	RICH.	OTTAWA	MAQUOKETA	Neda	0 – 15	Shale, red, hematitic, oolitic
					Brainard	0 – 100	Shale, dolomitic, greenish gray
					Ft. Atkinson	5 – 50	Dolomite and limestone, coarse grained; shale, green
		MA. / ED.			Scales	90 – 100	Shale, dolomitic, brownish gray
	CHAMPLAINIAN	TRENTONIAN		GALENA	Wise Lake - Dunleith	170 – 210	Dolomite, buff, medium grained
					Guttenberg	0 – 15	Dolomite, buff, red speckled
		BLACKRIVERAN		PLATTEVILLE	Nachusa	0 – 50	Dolomite and limestone, buff
					Grand Detour	20 – 40	Dolomite and limestone, gray mottling
					Mifflin	20 – 50	Dolomite and limestone, orange speckled
					Pecatonica	20 – 50	Dolomite, brown, fine grained
				ANCELL	Glenwood	0 – 80	Sandstone and dolomite
					St. Peter	100 – 600	Sandstone, fine; rubble at base
	CANADIAN		KNOX	PRAIRIE DU CHIEN	Shakopee	0 – 67	Dolomite, sandy
					New Richmond	0 – 35	Sandstone, dolomitic
					Oneota	190 – 250	Dolomite, slightly sandy; oolitic chert
					Gunter	0 – 15	Sandstone, dolomitic
CAMBRIAN	CROIXAN	TREMPEALEAUAN			Eminence	50 – 150	Dolomite, sandy; oolitic chert
					Potosi	90 – 220	Dolomite, slightly sandy at top and base, light gray to light brown; geodic quartz
		FRANCONIAN			Franconia	50 – 200	Sandstone, dolomite and shale; glauconitic
					Ironton	80 – 130	Sandstone, medium grained, dolomitic in part
		DRESBACHIAN			Galesville	10 – 100	Sandstone, fine grained
					Eau Claire (*Proviso Mbr*, *Lombard Mbr*, *Elmhurst Mbr*)	370 – 575	Siltstone, shale, dolomite, sandstone, glauconite
			POTS-DAM		Mt Simon	1200 - 2900	Sandstone, fine to coarse grained

Fig. 1 - Generalized columnar section of Cambrian and Ordovician strata in northeastern Illinois (from Buschbach and Bond, 1967, p. 21).

Procedure

Data taken in relatively deep drill holes were tabulated (tables 1, 2, and 3, appendix 2). Pertinent available information about all holes drilled to the St. Peter or deeper well within the Illinois Basin was included. Data on relatively shallow wells around the rim of the basin were not included.

The information that was collected included:

(1) Surface elevation
(2) Depth to top of aquifer investigated
(3) Depth to top of perforated zone
(4) Total dissolved solids and specific gravity of water samples recovered by swabbing or by pumping or in drill-stem tests
(5) Equilibrium water-level observations in wells
(6) Drill-stem test (DST) results
  (a) Gauge depth, top and bottom gauge
  (b) Initial and final closed-in pressures
  (c) Pressure extrapolated to shut-in time, θ, $= \infty$
  (d) Liquid fill-up during DST.

In tables 1, 2, and 3, column 10, the heading "observation point" needs a word of explanation. Generally we can calculate $H^{1.00}$ for only a few points in a well. The observation point may be the position of the drill-stem test pressure gauge, the reservoir pressure gauge, the top of the perforations in the casing, or the top of the open hole (casing seat). In some cases, for lack of better information, the observation point was taken to be the top of the DST interval or the top of the aquifer.

The quality of the data varied from very good to very poor. Generally data from all sources were tabulated; then, if reason existed for choosing one value in preference to another, a judgment was made about the value to be used. For example, a water level, carefully taken, was better than a drill-stem test result, especially if the rock had limited permeability. A water sample taken after extensive swabbing or pumping was better than a sample taken in a drill-stem test. However, all choices were not as clear cut as this. For example, sometimes a choice had to be made between the results of a relatively poor drill-stem test and the results of a water-level observation taken in a hole filled with water whose density was not known accurately.

The accuracy of well-head elevations was checked against topographic maps, well-log records, and other sources. In particular, an effort was made to insure that, for a given drill hole, the values used for depth of the water level, observation point in the aquifer, and depth of the pressure bomb were all measured with respect to the same elevation.

Calculation of $H^{1.00}$

The most significant quantity in this study is $H^{1.00}$, the head in terms of fresh water, with respect to sea level. When we say that $H^{1.00}$ has a given value, N, at an observation point, we mean that in a manometer tube containing water having a relative density of 1.00 and open at the observation point, the water would be in equilibrium with the water in the aquifer if the surface of the water in the manometer tube was at a level N feet above sea level. The procedures used in calculating $H^{1.00}$ are given in appendix 1.

Results

The present study gives information for about fifty locations in Illinois, central and eastern Iowa, southwestern Michigan, and northwestern Indiana. Included are data from about 20 gas-storage projects and 25 miscellaneous drill holes: oil and gas tests, holes drilled for gas-storage projects, and waste-disposal wells. Most of the observation points were more than 1,500 feet deep and ranged down to almost 12,000 feet deep (tables 1, 2, and 3).

In many gas-storage reservoirs, data are available for a number of wells. In tables 1, 2, and 3 usually data for only one well in each reservoir are listed; the well is generally the one that appears to be representative of the reservoir or the well for which the most complete information is available. In a few cases, averages or reasonable estimates are given. Because of the importance of Royal Center, to be explained later, most of the available data for that reservoir are presented in the tables.

The data on subsea depths, water levels, pressures, and water densities, as well as the derived values of $H^{1.00}$, can be presented in various ways. Figures 2, 3, and 4 show how subsea depth, water density, and $H^{1.00}$ vary from one location to another. Figures 5, 6, 7, and 8 are cross sections that show how these quantities vary as we go into or across the Illinois Basin.

In a general way, as we go from the northern part of Illinois toward the deeper part of the Illinois Basin, the values of $H^{1.00}$ in a given aquifer increase. The increase in $H^{1.00}$ is more pronounced for the Mt. Simon than for the Ironton-Galesville or the St. Peter. If the densities of these waters were uniform, we could conclude immediately that water flows toward the north from the deeper part of the basin.

But the densities of the waters, rather than being uniform, increase steadily southward, more or less paralleling the increasing values of $H^{1.00}$. Furthermore, evidence exists that at a given location the density of the water may be a function of depth. In a system like this, flow is not a simple function of hydrodynamic potential or of hydraulic head, but it depends upon many factors, as will be shown in the following section.

Some Factors That Affect Flow

This study was undertaken primarily to determine what flow, if any, occurs in the deep aquifers of the Illinois Basin. Flow in systems like these is complicated by many factors. Before we attempt to interpret the data on water levels, water densities, and pressures, we need to review some of the parameters that affect flow in such aquifers.

Potential.— In a system that contains water of uniform density, Hubbert's potential, ϕ, can be used to determine whether flow occurs. The rate of flow is a function of potential, permeability of rock, and viscosity of water, as shown by Hubbert (1953). On the other hand, in a system that contains water of variable density, only in certain simplified situations can the potential be used to determine whether flow occurs.

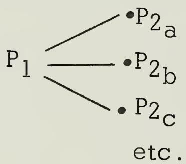
Hubbert's treatment assumes that no mechanical barriers to flow exist in the region under consideration. But a trough filled with dense water can be a barrier to flow; a number of small troughs in series can be just as effective a barrier as one large one. Potential can be used to make inferences about flow only if the effects of such troughs are known to be negligible.

Hydraulic head. — In general, for a system that contains water of variable density, flow can occur along a given flow path if

$$\psi_{\rho} = [\Delta H^{1.00} - \int_{P_2}^{P_1} (\rho - 1)\, dZ]$$

along the flow path is not zero. The direction of flow depends on the sign of the quantity ψ_{ρ}. The magnitude of this quantity is a measure of the net force available to cause flow (Bond and Cartwright, 1970). In the case of flow paths for which Z is constant, the criteria for flow are simplified; for such flow paths, a difference in head between two points is proof of flow between the points. Over an area that has no barriers to flow, at elevation Z, the head and the water density at this elevation are constant when the water is static.

Consider an aquifer in which $H^{1.00}$ and ρ vary from point to point:



The force available to cause flow from P_1 to P_{2a} is proportional to

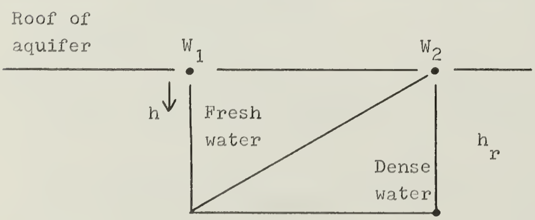
$$[\Delta H^{1.00}_{1,2a} - \int_{P_1}^{P_{2a}} (\rho - 1)\, dZ].$$

This force is a component of the total force vector acting on water along a line from P_1 to P_{2a}. The general direction of flow may be from P_1 toward P_{2a}, that is, from left to right. But the true direction of flow will be along the line where $[\Delta H - \int (\rho - 1)\, dZ]$ is at a maximum. If ρ and ΔH are known in detail, flow patterns over the area can be deduced. Generally ρ and ΔH are not known in detail; therefore, true flow patterns can be deduced only if simplifying assumptions are made.

Mixing zone. — Considerable mixing occurs when one water in an aquifer is displaced by another (Ogata, 1970). In the area studied, this mixing appears to have resulted in appreciable changes in composition and density of water within relatively small distances. The entire mixing zone appears to be about 50 to 100 miles wide.

Tilted interface. — Hubbert (1953, p. 1994) has shown that when fresh water flows above salt water in an aquifer, the interface between the two is tilted. When stratified water of variable density flows through an aquifer, it can be considered to have an infinite number of such tilted interfaces in which the angle of tilt decreases with depth.

Flow of light water along roof of aquifer. — Consider the simple case where the roof of the aquifer is flat and fresh water displaces water having a relative density ρ. Let $\Delta H^{1.00}$ be the difference between values of $H^{1.00}$ at locations W_1 and W_2 at the top of the aquifer. Let h be depth measured from



(Vertical scale is greatly exaggerated.)

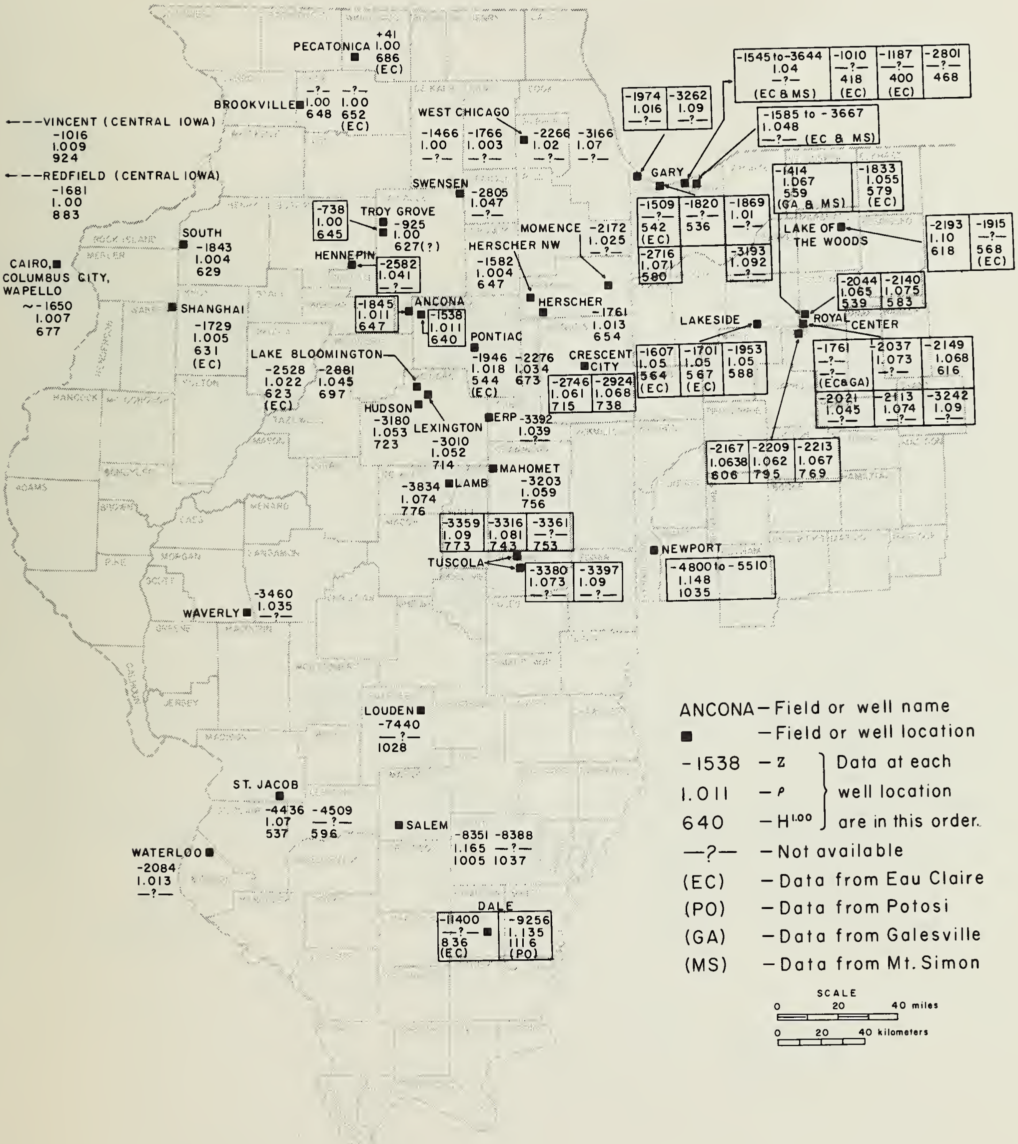


Fig. 2 - Z, ρ, and $H^{1.00}$ for observation points in the Mt. Simon.

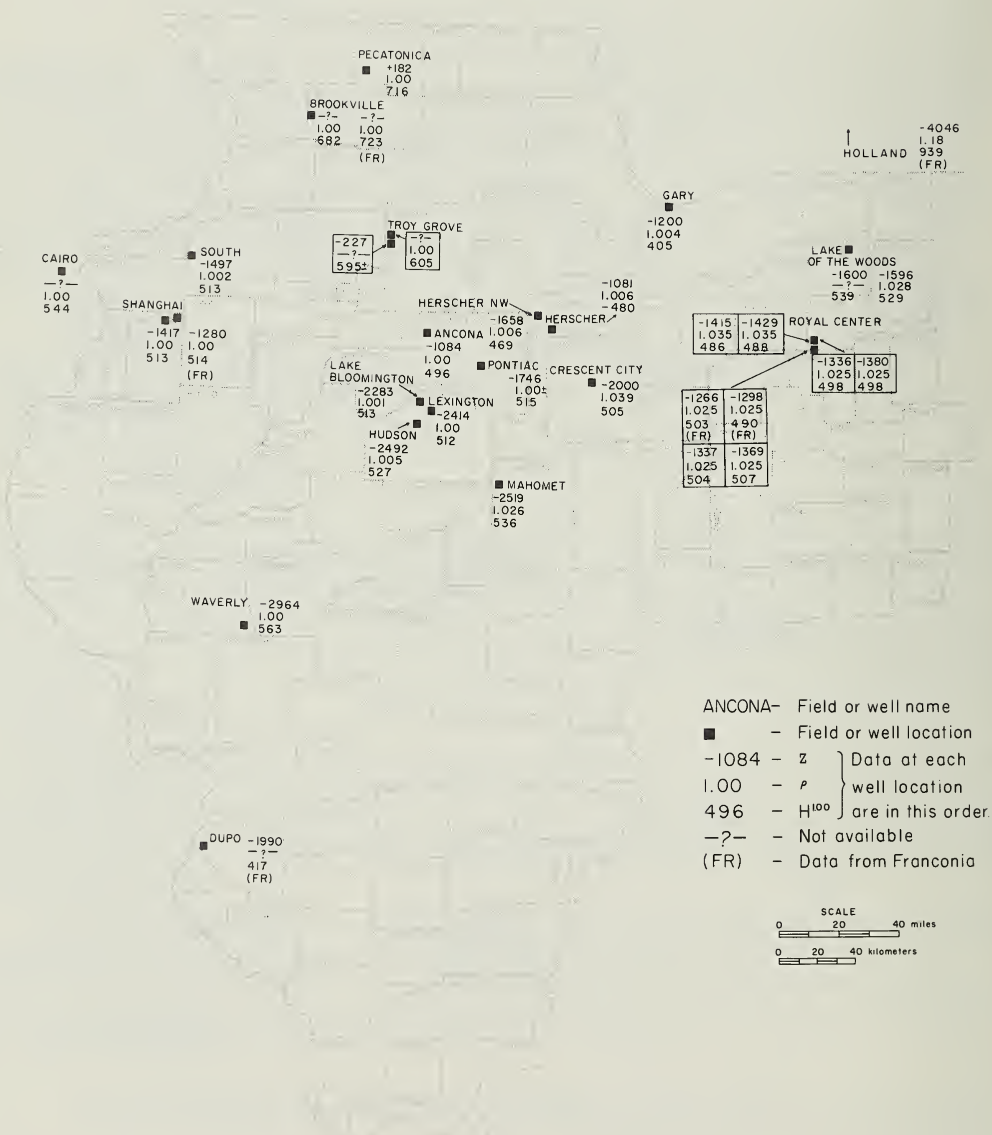


Fig. 3 - Z, ρ, and $H^{1.00}$ for observation points in the Ironton-Galesville.

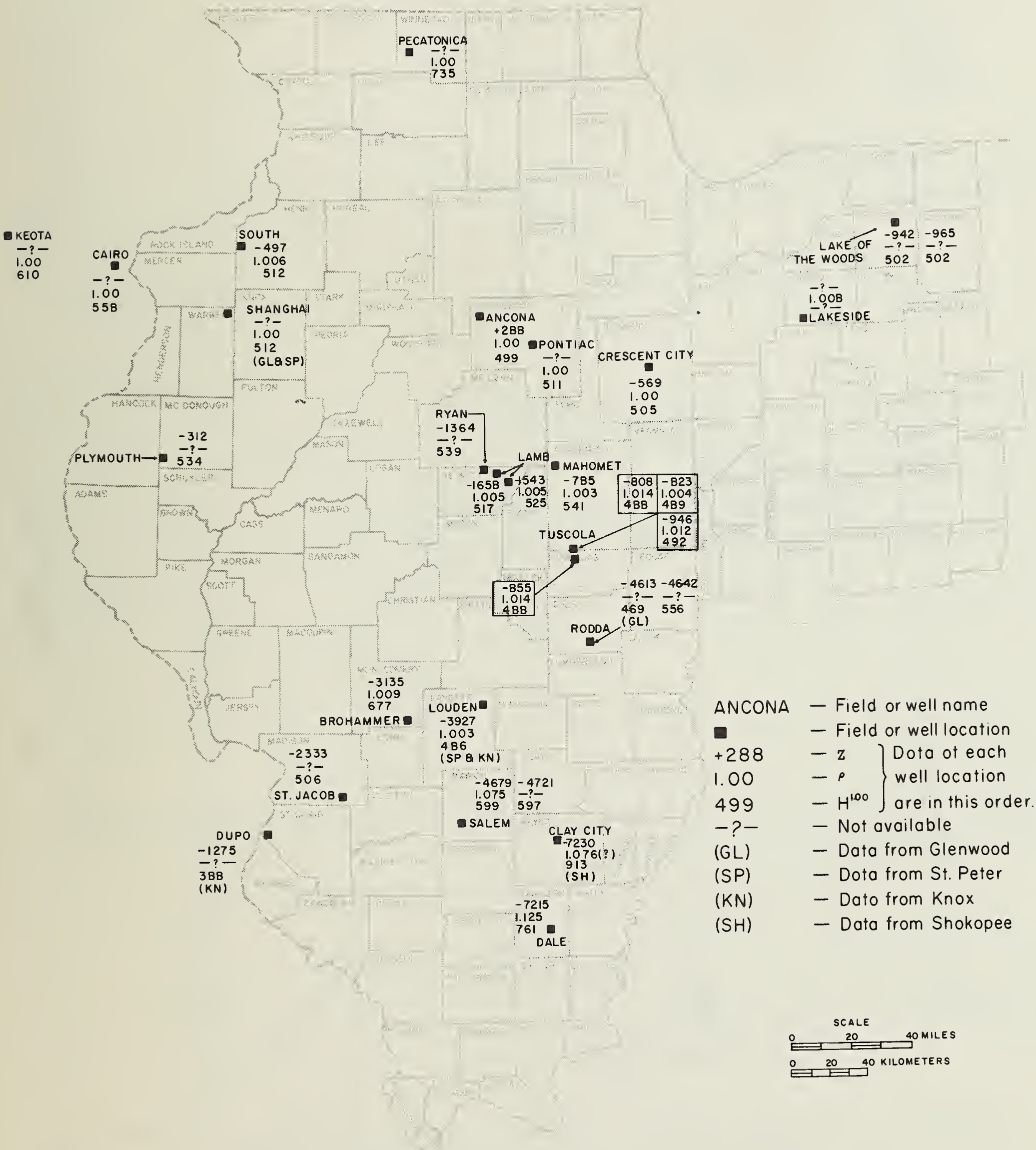


Fig. 4 - Z, ρ, and $H^{1.00}$ for observation points in the St. Peter.

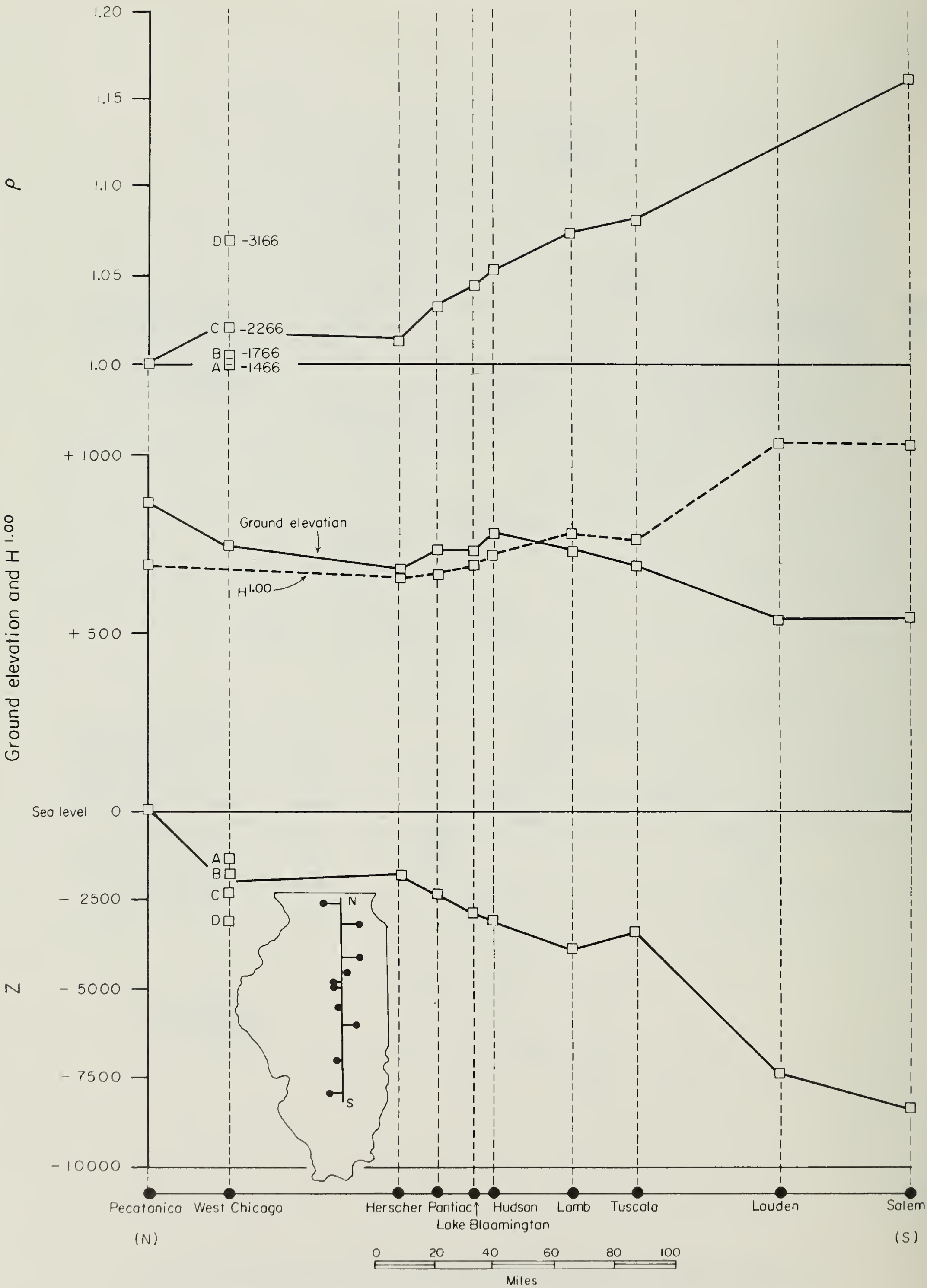


Fig. 5 - ρ, $H^{1.00}$, Z, and ground elevation for observation points in the Mt. Simon along N-S cross section. For West Chicago, data are given for four observation levels: A, B, C, and D. On the plot of values of ρ, the numbers opposite the boxes are values of Z for levels A, B, C, D.

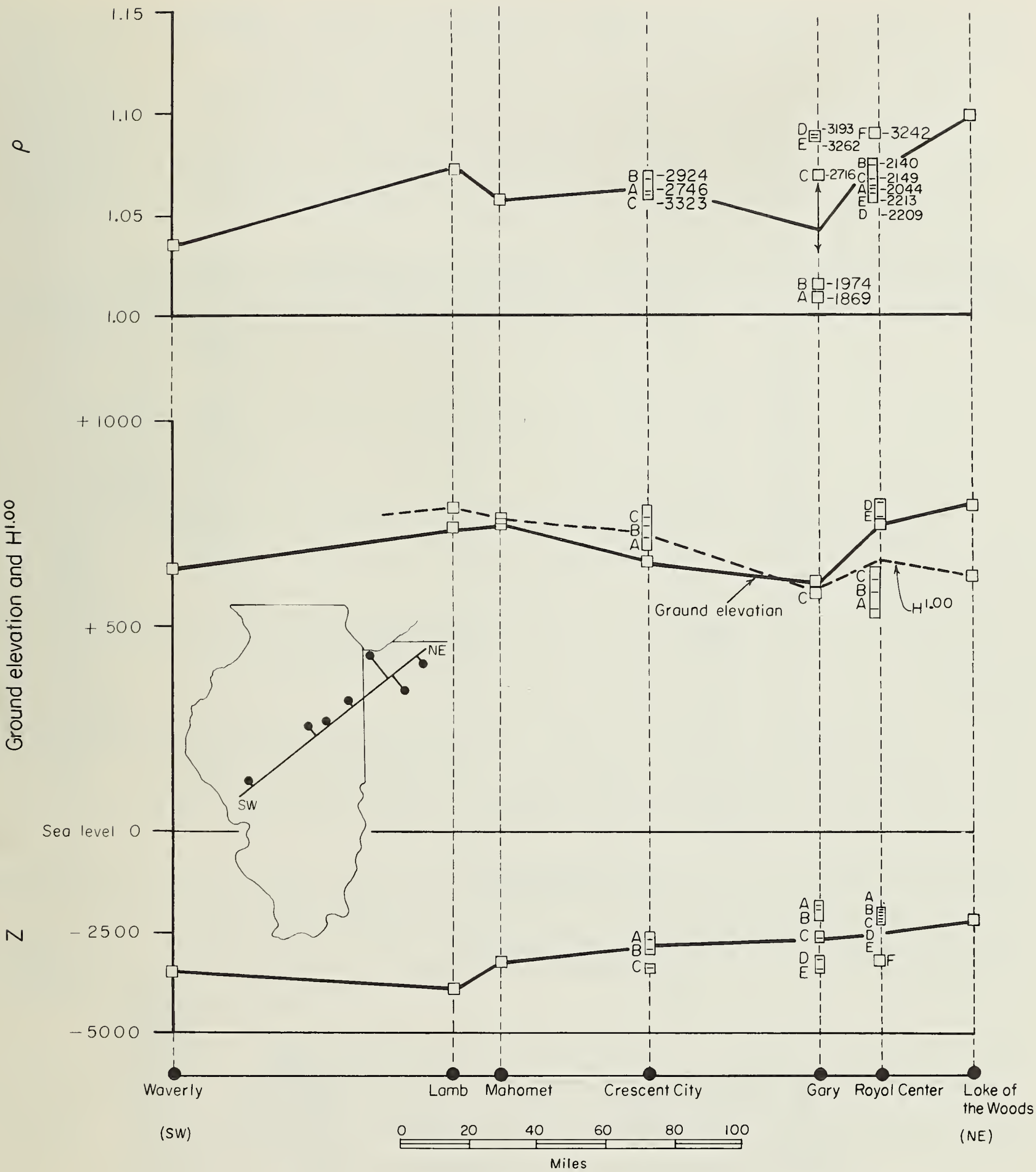


Fig. 6 - ρ, $H^{1.00}$, Z, and ground elevation for observation points in the Mt. Simon along NE-SW cross section. For Crescent City, Gary, and Royal Center, data are given for multiple observation levels: A, B, C.... On the plot of values of ρ, the numbers opposite the boxes are values of Z for levels A, B, C....

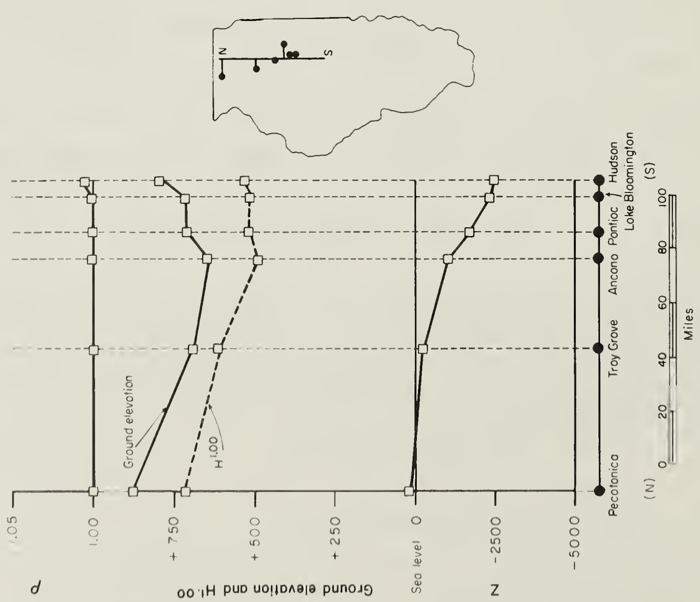


Fig. 7 - ρ, $H^{1.00}$, Z, and ground elevation for observation points in the Ironton-Galesville along N-S cross section.

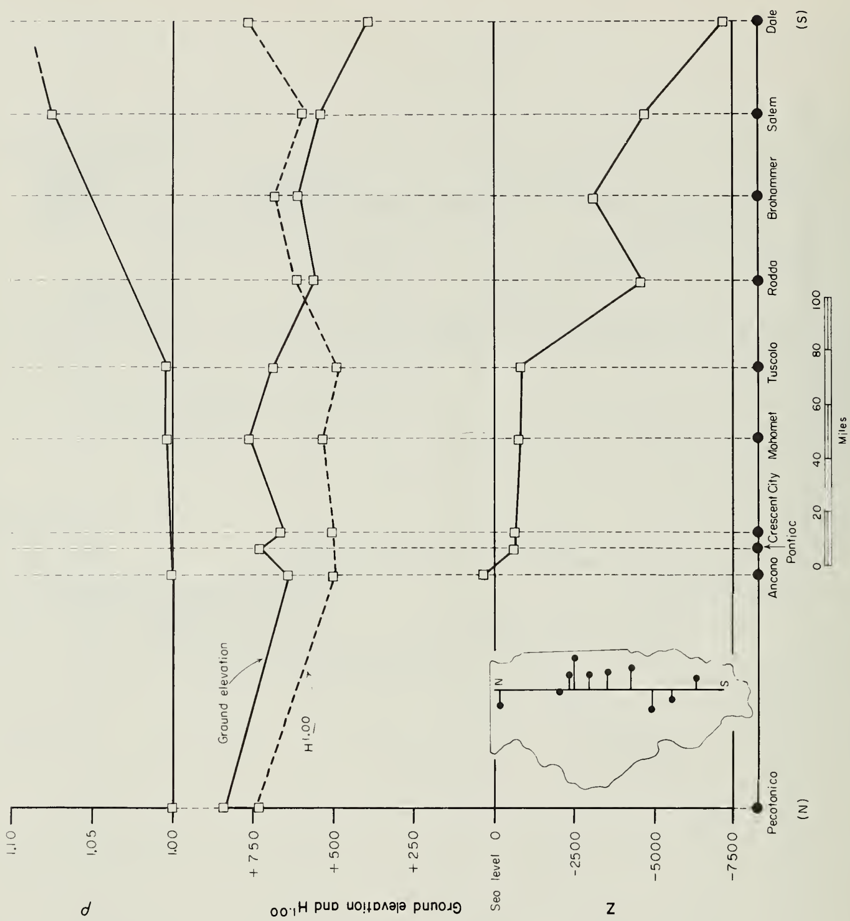
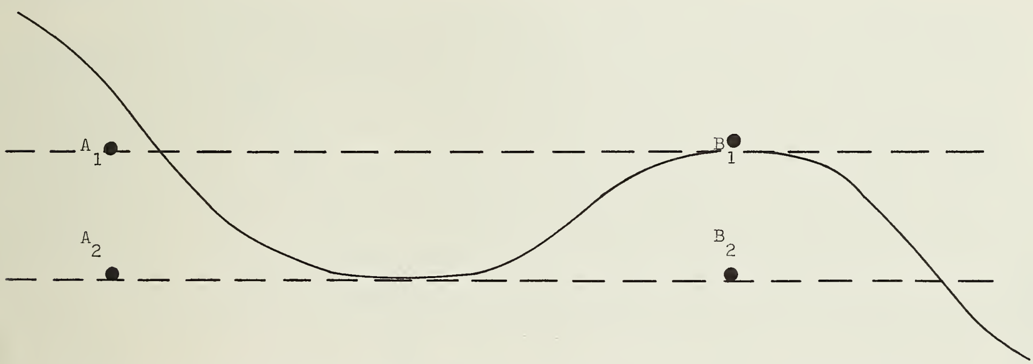


Fig. 8 - ρ, $H^{1.00}$, Z, and ground elevation for observation points in the St. Peter along N-S cross section.

the top of the aquifer. At W_2, at a depth h_r, given by $h_r \times (\rho - 1) = \Delta H^{1.00}$, the difference in $H^{1.00}$ is just balanced by the excess weight of the column of dense water; therefore, no appreciable flow occurs at this depth or at greater depths. The thickness of the aquifer is assumed to be large in comparison with h_r. At depths between 0 and h_r, flow rate is proportional to $(h_r - h)$. (The effects of the mixing of fresh and dense waters are ignored here.) Therefore, at the leading edge of the displacement front, flow occurs along the roof of the aquifer. Thus, the direction of flow in such systems is greatly influenced by structure.

Difference in head across a saddle.— As relatively light water displaces heavier water near a saddle, differences in $H^{1.00}$ can be caused by the differences in water density on either side of the saddle.



The difference in head at points A_1 and B_1, $\Delta H^{1.00}\ A_1, B_1$, is given by

$$\Delta H^{1.00}{}_{A_1,B_1} = \left[\int_{B_1}^{B_2} (\rho - 1)\, dZ - \int_{A_1}^{A_2} (\rho - 1)\, dZ\right].$$

That is, the head at point A_1 exceeds the head at point B_1 by the amount $\Delta H^{1.00}_{A_1,B_1}$.

In a similar way, differences in $H^{1.00}$ can exist between points inside and outside a dome. Thus, differences in head can exist, even if no flow occurs. Or if flow does occur, these differences in head can affect the forces available for causing flow.

Troughs — "corrugated flow".— As shown by Bond and Cartwright (1970), a trough can cause a difference in $H^{1.00}$ if the water is stratified, even though no flow occurs. If flow does occur, the force available to cause flow can be decreased. When flow occurs through a series of troughs ("corrugated flow"), these effects are additive. Diffusion effects are assumed to be negligible.

These are some of the parameters that must be taken into account when water level, water density, and pressure data are used to study flow in such complex aquifers.

Conclusions From Present Study

Water Composition and Density

For the brines that were studied, relative density was found to be approximately proportional to the concentration of dissolved solids (fig. 9). Figure 9

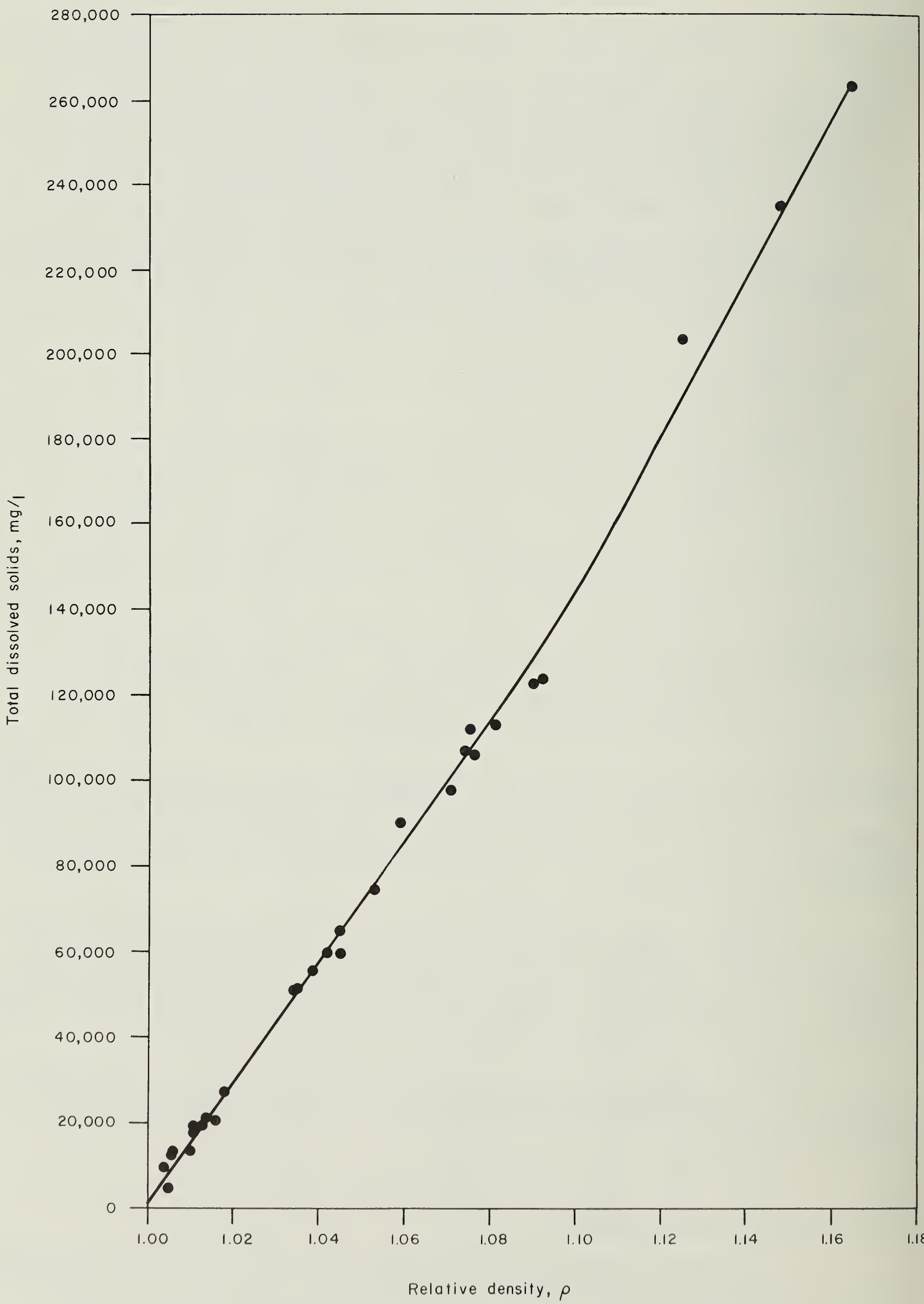


Fig. 9 - Relation between relative density and dissolved-solids content of brines in deep aquifers of the Illinois Basin.

was used to obtain an estimate of the relative density in cases where only the concentration of dissolved solids was known. Relative densities estimated in this manner are designated $\rho_{est.}$ in tables 1, 2, and 3. In figure 9 and elsewhere in this report the concentration of dissolved solids is expressed in terms of milligrams per liter. For dilute brines, the number of milligrams per liter (mg/l) is approximately equal to the number of parts per million by weight (ppm). For more concentrated brines, mg/l = ppm x ρ .

Tables 1, 2, and 3 include some data on brines from the Michigan Basin. Since the composition of these brines differs considerably from that of Illinois Basin brines, data on Michigan Basin brines were not plotted in figure 9.

Mt. Simon Aquifer

Density of water vs. subsea depth.— The Mt. Simon Sandstone and a relatively permeable sandstone widely present at the base of the Eau Claire Formation are hydrologically connected and are considered as one unit, called the Mt. Simon Aquifer (Suter et al., 1959). In this report the term Mt. Simon is used to refer to the aquifer and not to the stratigraphic unit. Along a line from about West Chicago to Tuscola, the relative density of the Mt. Simon water is approximately a linear function of subsea depth (fig. 10). As we move westward from this line, the density becomes smaller at a given elevation; as we move eastward, the density becomes greater at the same elevation.

A hypersurface was fitted to the data presented in figure 10. The hypersurface, which has the form of a truncated power series in the spatial coordinates x, y, and z:

$$\rho * (x, y, z) = a_1 + a_2x + a_3y + a_4z + a_5x^2 + a_6y^2 + a_7z^2 + \ldots$$

(Heigold, Mast, and Cartwright, 1971), provides a continuous relative density function approximation to the observed data. In the present study the hypersurface was limited to the third order (20 terms). A trend surface (Sutterlin and Brigham, 1967) permits one to approximate a power series to values of a quantity that is a function of two independent variables. A hypersurface permits one to approximate a power series to values of a quantity that is a function of three or more independent variables. In the present case the relative density, ρ , is a function of latitude, longitude, and depth.

The hypersurface that was referred to above was used to evaluate ρ at several values of Z to give the density distributions within the surfaces defined by these values of Z.† These relative density distributions were used to obtain the iso-density lines presented in figure 11, A-G. This figure also gives the corresponding concentrations of dissolved solids (mg/l); therefore, an estimate of the concentration or of the relative density can be made for water from any depth at a given location. The dashed lines in figure 11, A-G, show the extrapolation of the calculated iso-density lines into regions where the top of the Mt. Simon Aquifer is below the given value of Z. These lines can be used to make a rough estimate of the salinity to be expected in aquifers directly above the Mt. Simon, if the assumption can be made that these aquifers are hydraulically connected with the Mt. Simon.

The data in figure 11, A-G, are presented in a different fashion in figure 12, A-G, which shows the depths at which a selected value of relative density

†The fitting of the hypersurface and the calculation of the relative density distributions were done by Paul Heigold.

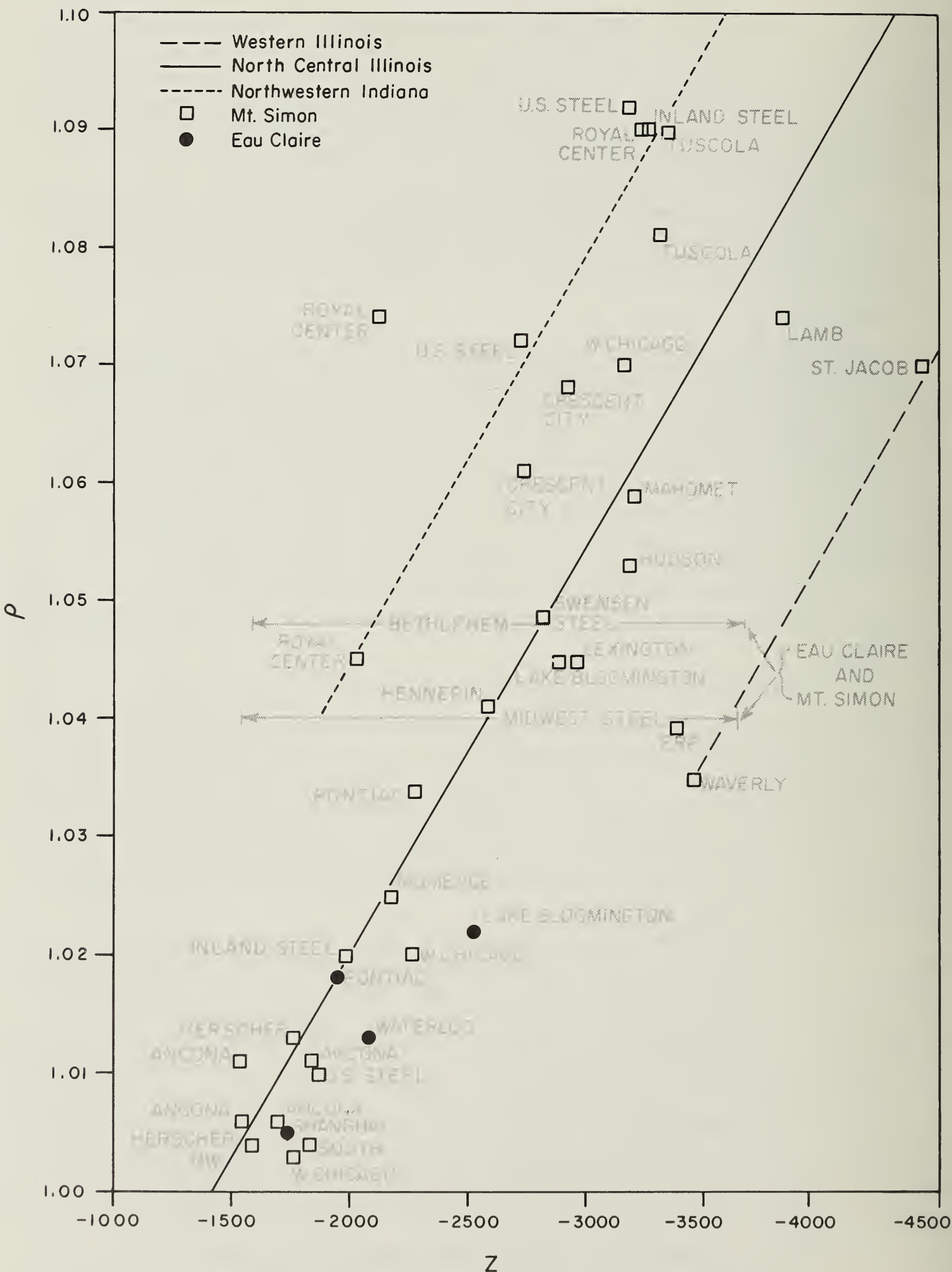


Fig. 10 - Relation between ρ and Z for waters from the Eau Claire and the Mt. Simon in the Illinois Basin.

(or of salinity) is found at different locations. If we assume that the Mt. Simon water is made up of a number of incremental layers increasing in density with depth, we can visualize from figure 12 the tilting of the interfaces between these incremental layers as Mt. Simon brine is displaced by fresh water.

Flow in the Mt. Simon Aquifer.— As stated above, in an aquifer that contains water of variable density we can determine whether flow occurs between two points only if we know (1) how ρ changes with respect to Z along possible flow paths between the two points, and (2) the head at each point. In the Mt. Simon, at a given location the density can be assumed to be a linear function of depth, within moderate depth intervals. Also, at a given subsea depth the density probably can be assumed to vary linearly with distance, over short distance intervals. Therefore, the value of the quantity

$$\Psi_{\rho_{ave.}} = [\Delta H^{1.00} - (\rho_{ave.} - 1)\Delta Z]$$

should indicate the general direction of flow and the approximate magnitude of the net force available to cause flow. (This force will generally be at an angle to the actual direction of flow; thus, it represents only one component of the total force.)

This conclusion is based on a highly simplified picture of the Mt. Simon Aquifer. Essentially it assumes that the aquifer is contained between two saucers. The effects of saddles, domes, troughs, and corrugations described above are ignored. Where sufficient data are available, this procedure should give essentially the same results as the procedure described by McNeal (see p. 4).

In figure 13 arrows are drawn whose lengths are proportional to $\Psi_{\rho_{ave.}}/s$ for pairs of observation points. If other parameters, such as viscosity, permeability, and porosity, can be assumed to be constant, the length of a given arrow is a measure of the possible flow rate in the direction of the arrow. Of course, the actual direction of flow within the aquifer may not be in the direction of the arrow; the direction given is that of one component of the total flow vector.

The quantity Ψ_{ρ_i} was also calculated using extreme values of ρ_i rather than $\rho_{ave.}$ That is, for two points, P_1 and P_2, the assumption was made that all of the water in the aquifer between P_1 and P_2 had the same relative density, ρ_1, as the water at P_1; Ψ_{ρ_1} was then calculated. Likewise, the assumption was made that all of the water between P_1 and P_2 had the same relative density, ρ_2, as the water at P_2, and Ψ_{ρ_2} was calculated. In a few cases such assumptions of extreme density values resulted in a reversal of the indicated direction of flow. This reversal occurred with the following pairs of points: Hudson and the South well, Crescent City and Herscher Northwest, Hudson and Ancona, Lamb and Pontiac, and St. Jacob and Salem. In all cases except the last pair, St. Jacob and Salem, the residual head was insignificant. In the case of flow between St. Jacob and Salem, a considerable flow vector from Salem to St. Jacob was indicated when the assumption was made that all of the water between the two points had the density of the water at Salem; over the elevation interval between the two observation points (about 4,000 feet), this assumption with respect to density probably is not warranted. Probably the directions given in figure 13 are reasonable indicators of the general directions of the forces available to cause flow.

For various reasons, to be discussed later, the McLean County-Livingston County area is of particular interest. Therefore, in figure 14, values of $\Psi_{\rho_{ave.}}/s$ for this area are presented in some detail. This figure also gives the directions of flow that have been inferred from water-level measurements within three gas-storage reservoirs.

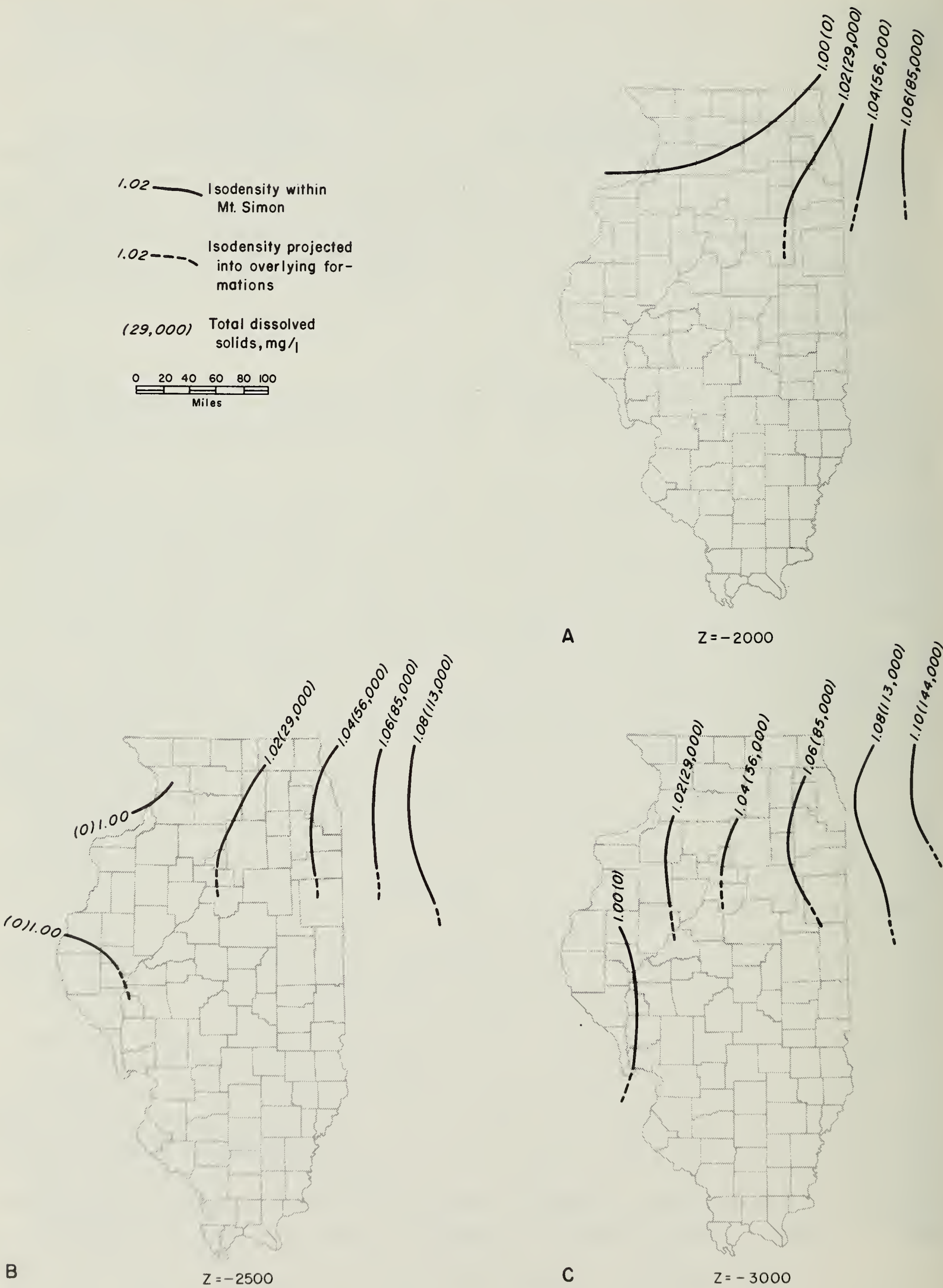
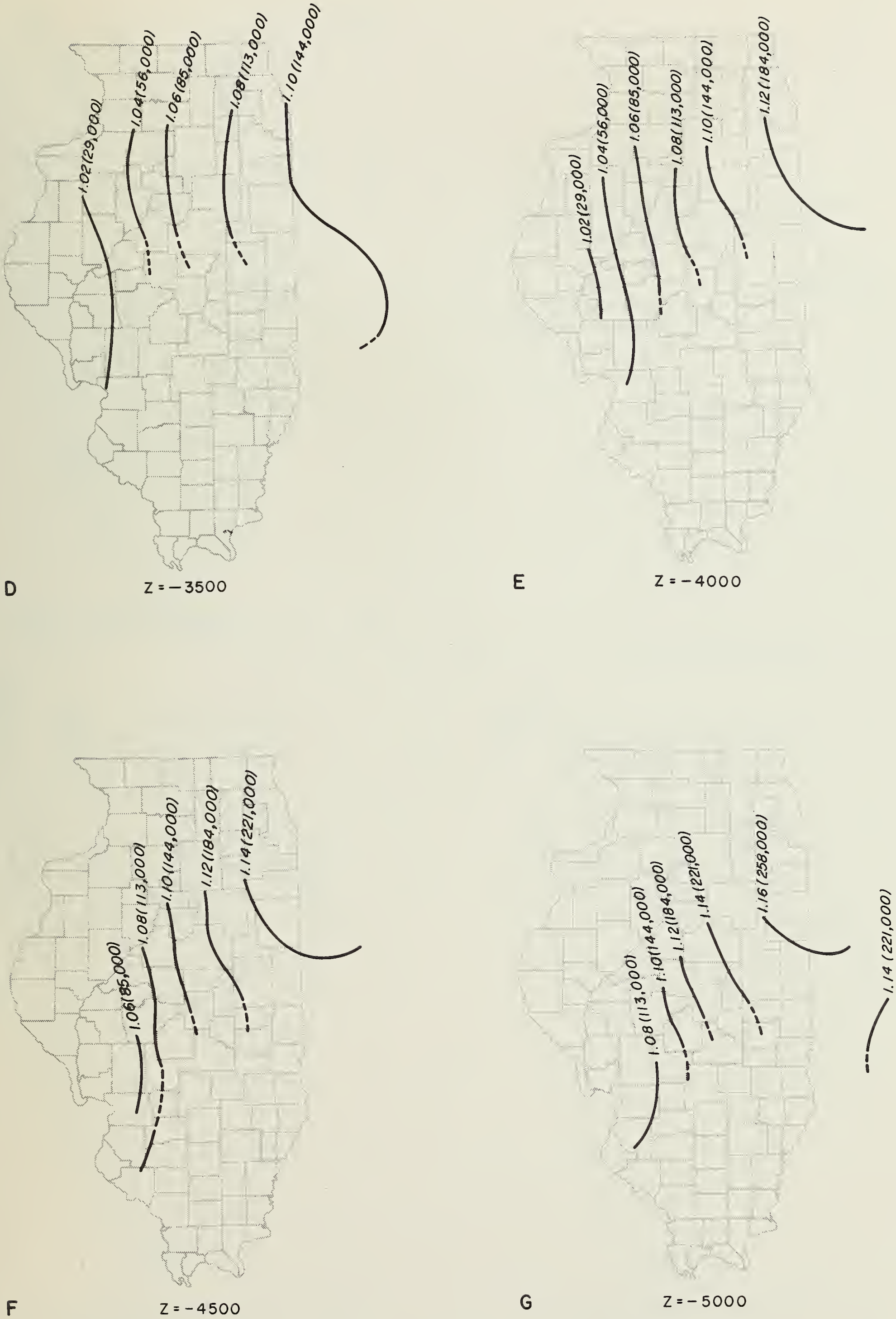


Fig. 11 - Relative density of



Mt. Simon water at various values of Z.

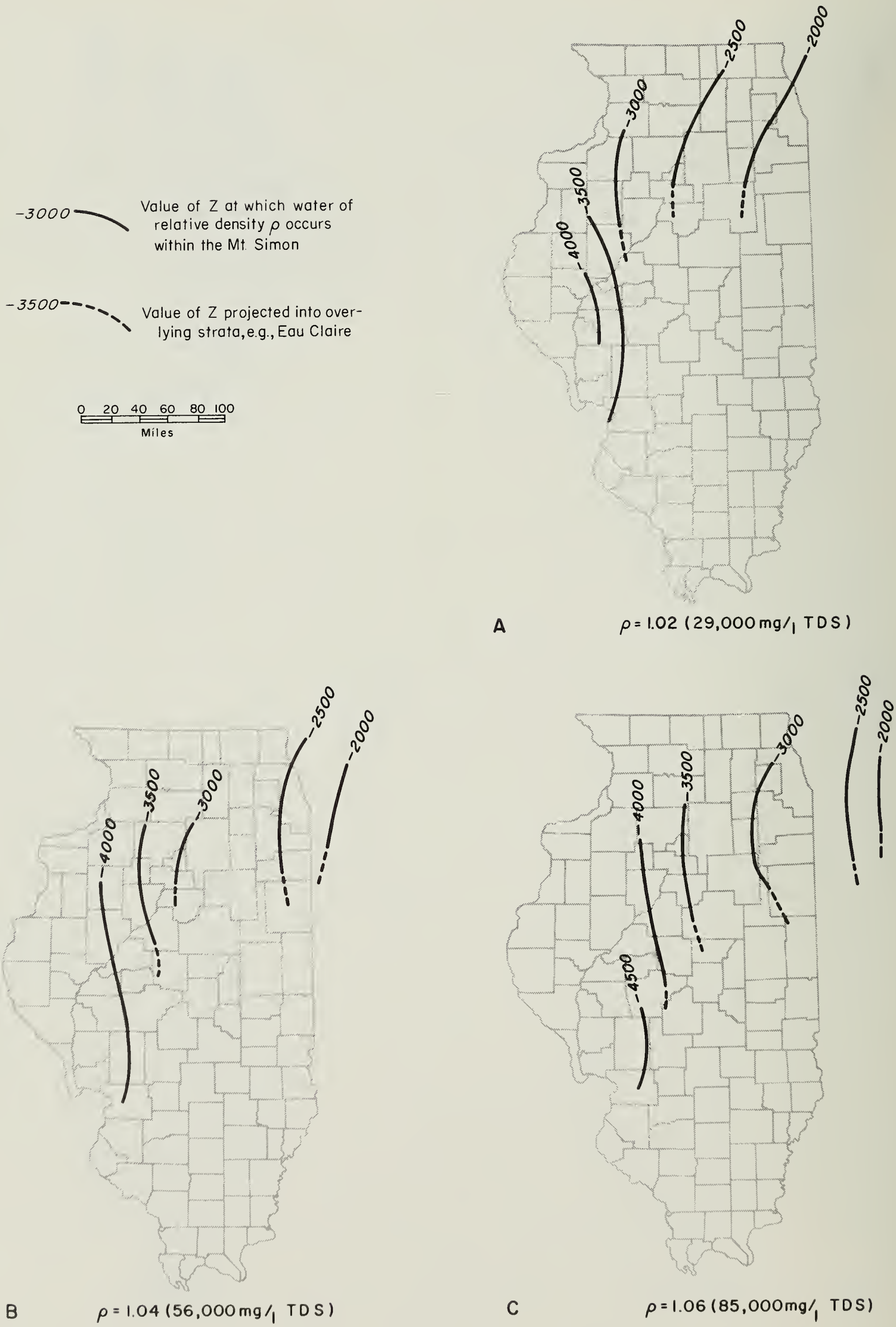
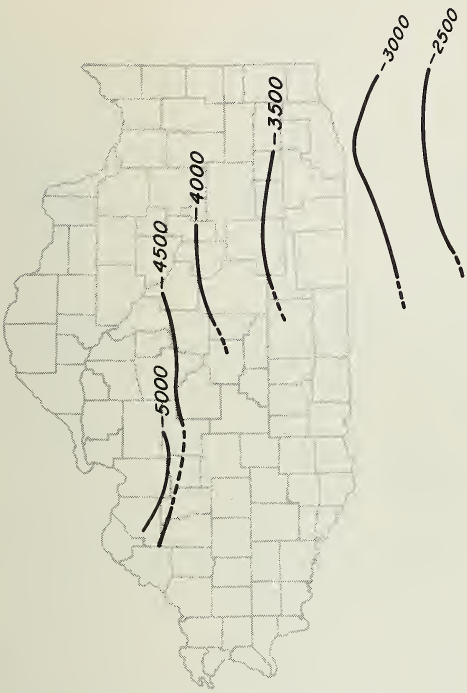
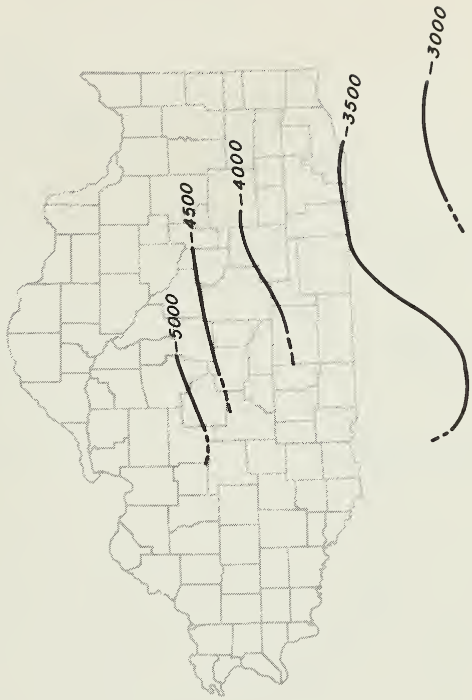


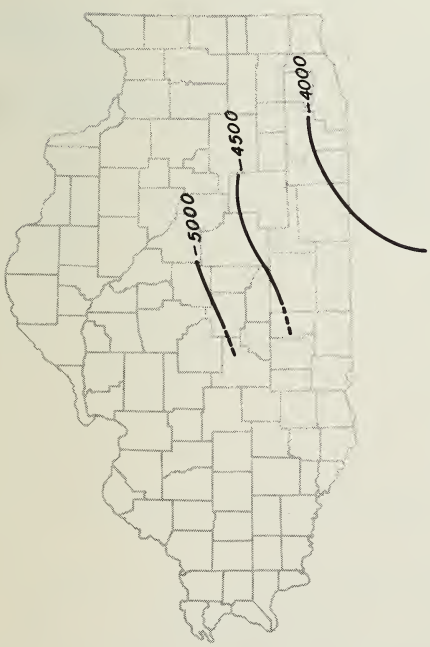
Fig. 12 - Value of Z at which water



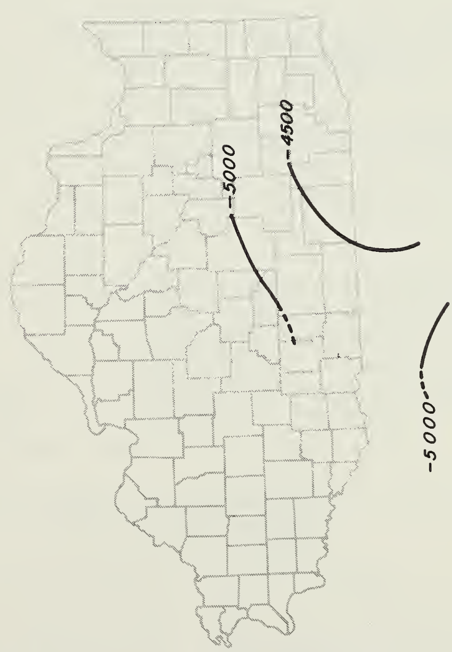
D $\rho = 1.08$ (113,000 mg/l TDS)



E $\rho = 1.10$ (144,000 mg/l TDS)



F $\rho = 1.12$ (184,000 mg/l TDS)



G $\rho = 1.14$ (221,000 mg/l TDS)

of given density occurs in the Mt. Simon.

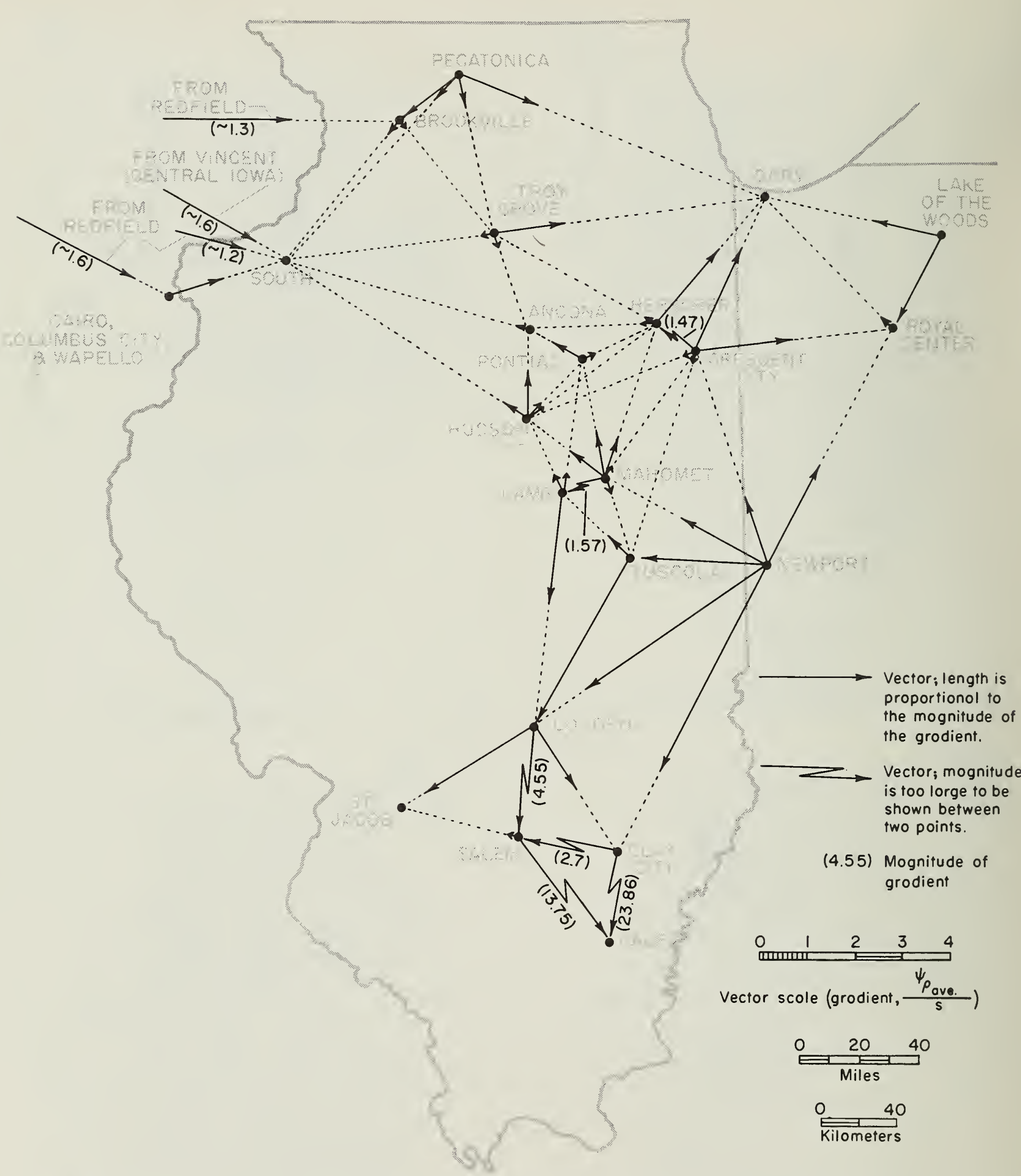


Fig. 13 - ($\psi_{\rho_{ave.}}$)/s for pairs of points in the Mt. Simon. Arrows indicate general direction of flow. Length of arrows is proportional to net force available to cause flow. (Data for Dale and Clay City are for the Eau Claire and the Knox, respectively.)

As far as flow in the Mt. Simon Aquifer in the northern part of Illinois is concerned, the water-density data (figs. 10, 11, and 12) are subject to two possible interpretations. On the one hand, the data are consistent with the idea that fresh water, moving from the west and northwest toward the east, has displaced a heavy brine. On the other hand, the data fit the assumption that brine, moving from the east to the west, has displaced fresh water. By means of the

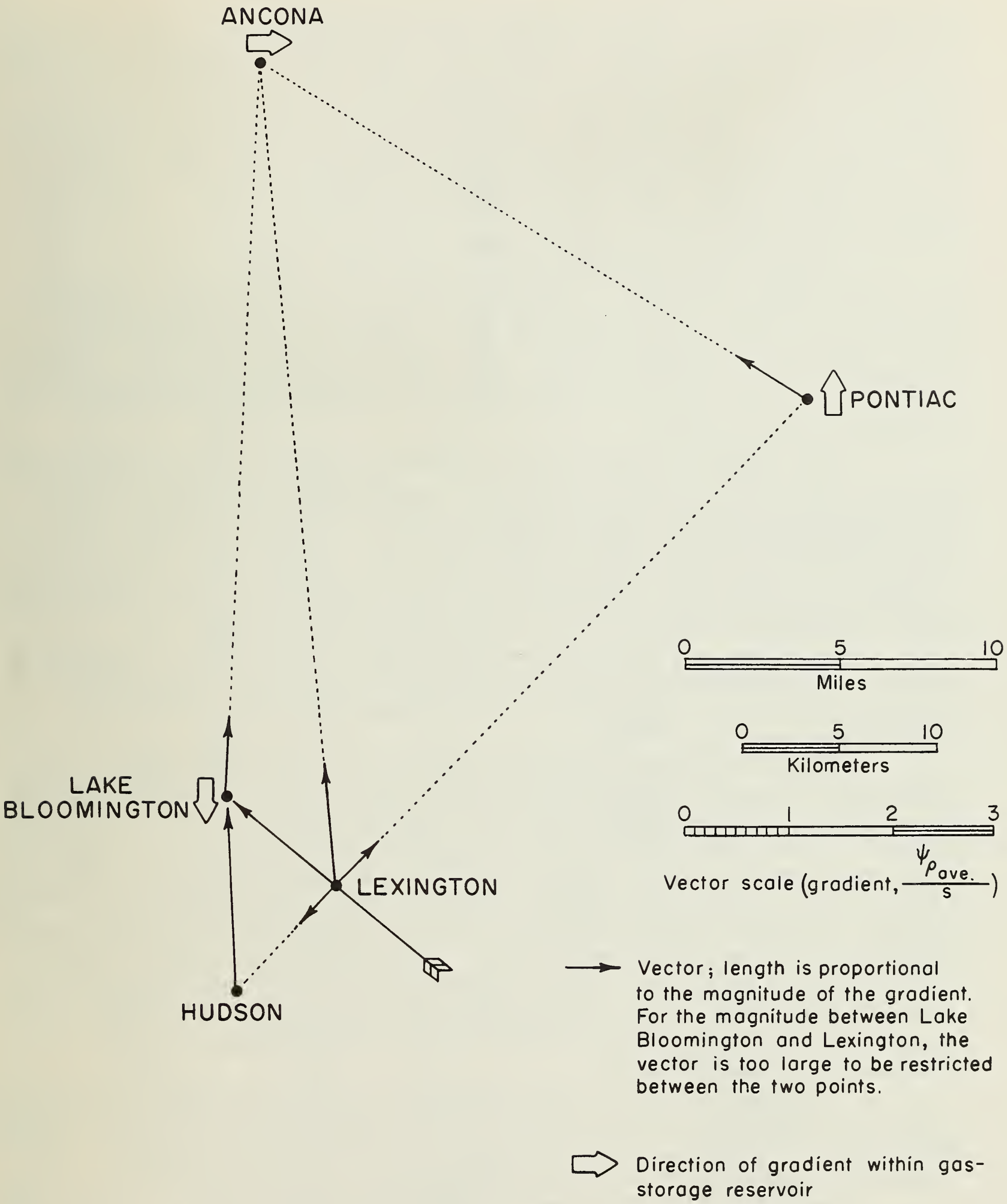


Fig. 14 - ($\psi_{\rho\,ave.}$)/s for pairs of points in the Mt. Simon in Livingston and McLean Counties, Illinois.

density data alone, one cannot determine which of these two interpretations is correct. But the water-density data, together with the data on $H^{1.00}$, can give an indication of the direction of flow.

The data in figure 13 indicate appreciable flow rates in the Mt. Simon Aquifer from northeastern Illinois into northwestern Indiana. The observed dif-

ferences between $H^{1.00}$ values for Herscher and Crescent City, on the one hand, and for Gary and Royal Center, on the other, could result, even though the water were static, if a trough existed. One trough about 1,000 to 2,000 feet deep (or several smaller troughs in series), with fresh water on one side and water of relative density 1.10 on the other, would be required to cause the differences in $H^{1.00}$ that are observed. From what is known about the area, this condition does not appear likely. Probably the observed differences in $H^{1.00}$ and ρ are proof of flow through the Mt. Simon toward the east and northeast in this area, that is, northwestern Indiana and the adjoining part of Illinois.

At Royal Center, $H^{1.00}$ at the top of the Mt. Simon is about 40 to 50 feet greater than in the Ironton-Galesville (fig. 15). This is approximately the amount of head required to lift the Mt. Simon water ($\rho = 1.07$) up through the 600± foot interval between the Mt. Simon and the Ironton-Galesville. Thus, if conduits for flow exist, Mt. Simon water can move from the Mt. Simon Aquifer up into the Ironton-Galesville at Royal Center. The data taken at Lakeside strengthen this conclusion.

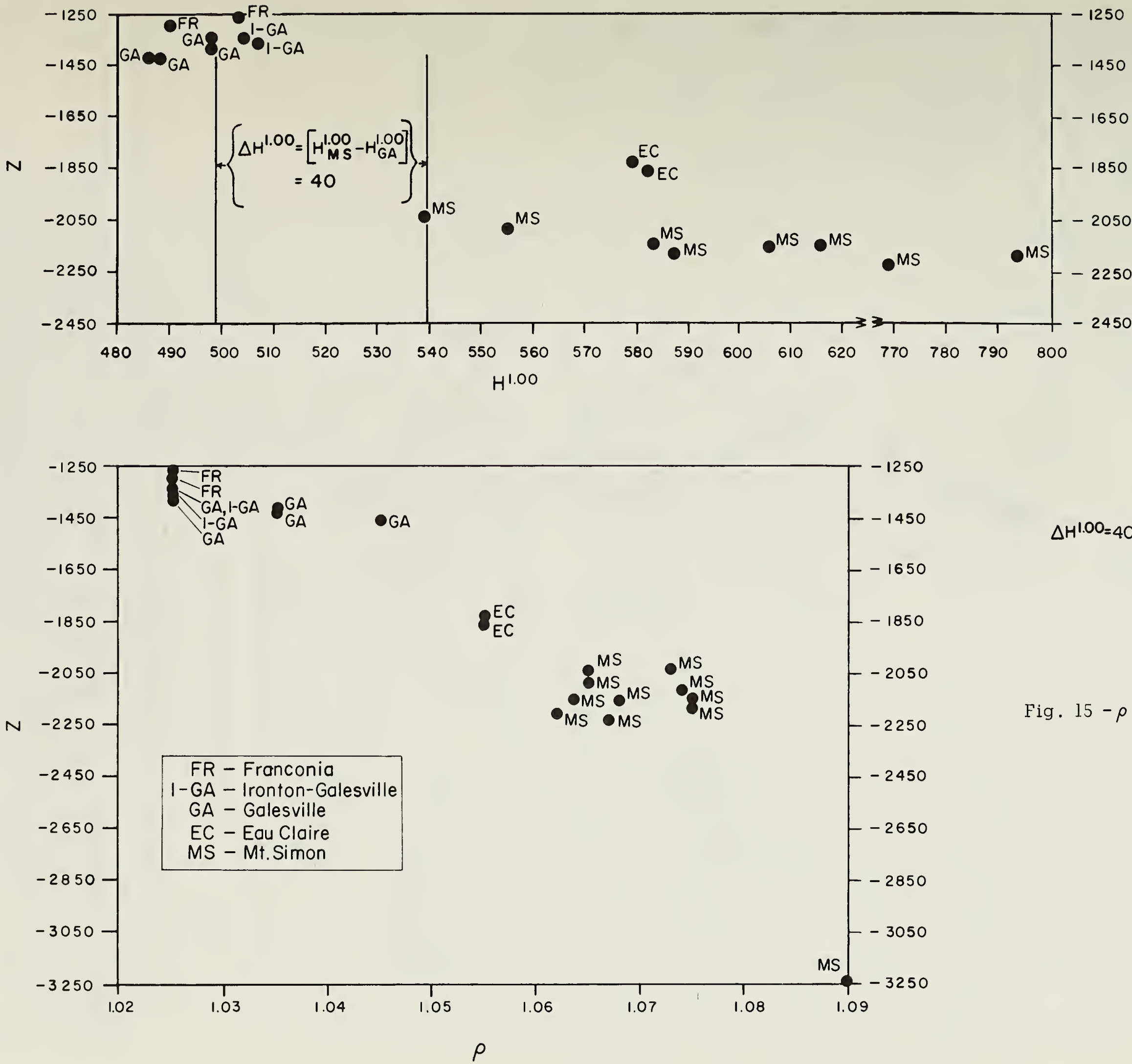
Such conduits for flow might be supplied by faults in the strata between the Mt. Simon and the Ironton-Galesville. Considerable information is available concerning faulting in the northwestern corner of Indiana (Dawson, 1952; Pinsak and Shaver, 1964; Swann, 1968; Bond et al., 1971). The Royal Center Fault is located near the Logansport Sag (fig. 16). Swann (1968, p. 12) shows a fault in the Jasper Sag, northwest of the Royal Center Fault. Thus, faults do exist, which may or may not serve as conduits for flow of water.

The information given earlier about water density and $H^{1.00}$ indicates that Mt. Simon water is flowing from northeastern Illinois into northwestern Indiana, then upward through the fault system in that area into the Ironton-Galesville.

In most of northern Illinois the water in the Ironton-Galesville is relatively fresh. However, at Crescent City the Ironton-Galesville water contains 56,000 mg/l of dissolved solids and has a relative density of 1.039. At Crescent City $H^{1.00}$ in the Mt. Simon Aquifer is about 220 feet greater than $H^{1.00}$ in the Ironton-Galesville; after allowance is made for the head required to lift Mt. Simon water up to the Ironton-Galesville, a net difference in head amounting to 170 feet remains. Evidently leakage from the Mt. Simon to the Ironton-Galesville has not occurred in the vicinity of Crescent City. Apparently the saline water that has flowed upward from the Mt. Simon to the Ironton-Galesville through the northwestern Indiana faults has run down gradient through the Ironton-Galesville under the influence of gravity and has displaced fresh Ironton-Galesville water, at least as far as Crescent City.

Suter et al. (1959, p. 54) have shown that heavy pumpage from the Ironton-Galesville has greatly lowered the piezometric surface in the area around Chicago. Presumably this pumpage has resulted in some lowering of the head in the Ironton-Galesville at points as far away as Royal Center.

The flow of Mt. Simon water up through the fault system in northwestern Indiana might have been caused by the reduction in head that has resulted from pumpage from the Ironton-Galesville in the Chicago area. However, in northern Illinois the pattern of water densities in the Mt. Simon Aquifer indicates that fresh water has moved eastward through the Mt. Simon, displacing brine and mixing with the brine for a distance of 50 to 100 miles.



$$\Delta H^{1.00} = 40 \approx (\rho_{MS} - 1)\Delta Z = (1.07 - 1) \times 600 = 42$$

Fig. 15 - ρ and $H^{1.00}$ in Royal Center aquifers.

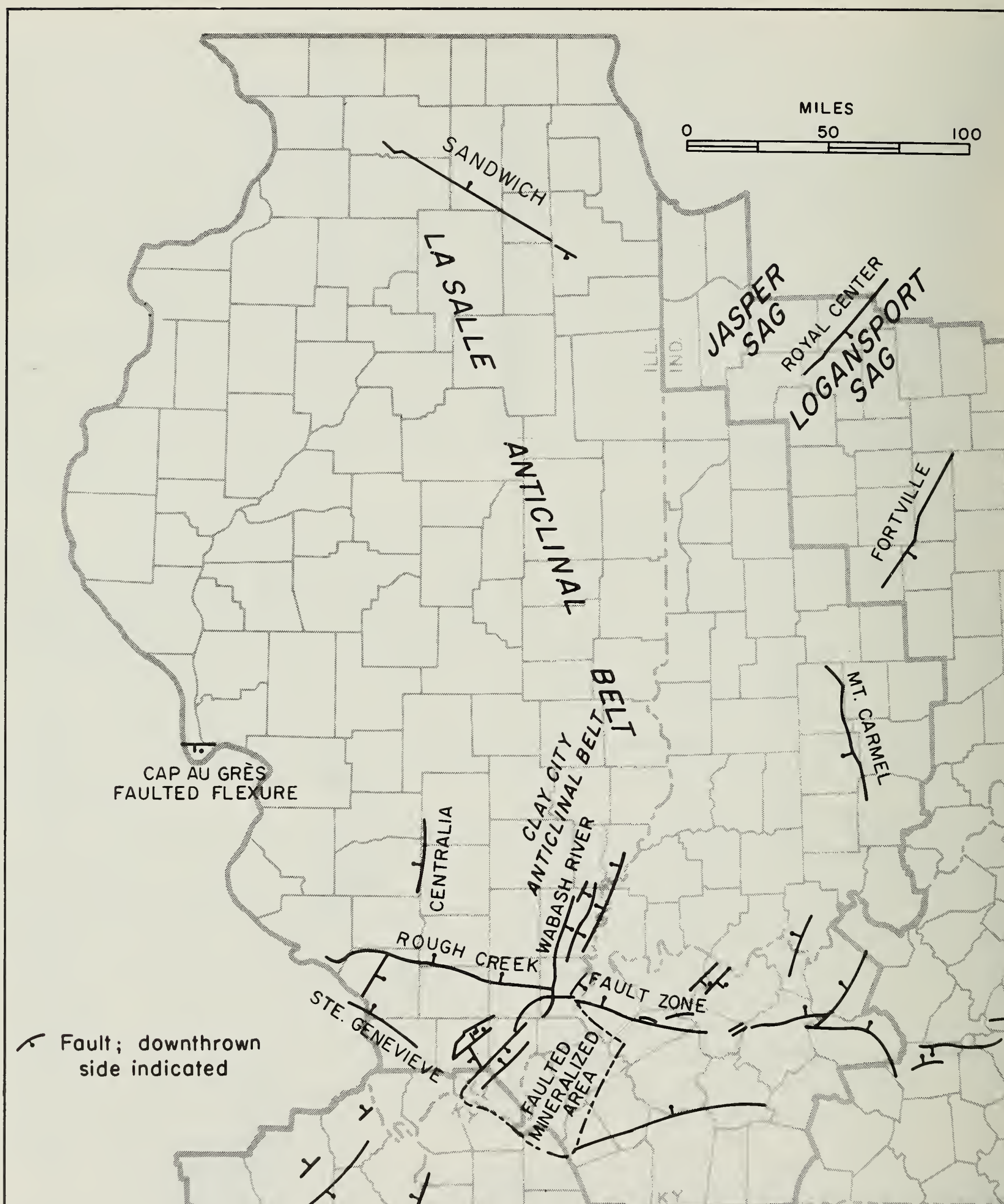


Fig. 16 - Major faults and some anticlinal belts in the Illinois Basin.

Estimates have been made of the rates of movement of this water under the influence of the observed heads (corrected for density effects) in the Mt. Simon.* These show that the water moves a few inches per year. At this rate, a million years or so would be required for the water movement that is inferred from

*The rate of advance (in./yr) = $\frac{2.27 \times \text{gradient } (\Delta H^{1.00}/\text{mi}) \times \text{permeability (darcys)}}{\text{porosity (fraction)} \times \text{viscosity (centipoises)}}$.

our data. Evidently the major movement in the Mt. Simon has not been caused by pumpage from the Ironton-Galesville in modern times, but rather it is the result of long-term natural forces.

An estimate has been made also of the rate of movement to be expected as dense water flows through the Ironton-Galesville southwestward from the Royal Center area under the influence of gravity alone. That is, dense Mt. Simon water (ρ = 1.045 to 1.070) was assumed to flow upward to the Ironton-Galesville and then settle as a result of the density contrast between this dense water and the original Ironton-Galesville water. In this case, too, a rate of a few inches per year was obtained, leading to the conclusion that about one million years would be required for this dense water (assumed to come from the Mt. Simon by way of the fault system) to flow through the Ironton-Galesville from the Jasper Sag to Crescent City. This agrees with the conclusion reached above about the time required for the displacement of brine by fresh water in the Mt. Simon. Probably water has flowed naturally through the Mt. Simon, then up through the faults and down along the bottom of the Ironton-Galesville for many years.

Of course, the flow of water in the Mt. Simon Aquifer might have been accelerated if the gradients in $H^{1.00}$ at some time in the past were much larger than at present. For example, glaciation might have greatly changed the potential for flow, as postulated by McGinnis (1968).

One can also speculate that the weight of the glaciers during Pleistocene time compressed the sedimentary rocks in the Illinois and the Michigan Basins and thereby caused a flexure of the rocks across the arch separating the two basins. Perhaps this flexure was sufficient to cause vertical fractures through which water could flow from the Mt. Simon to the Ironton-Galesville.

Although saline water appears to have flowed in the Ironton-Galesville of northwestern Indiana and part of northeastern Illinois under natural forces for many years, no doubt in modern times flow of this saline water has been influenced by man-made forces. Rough estimates indicate that flow of the saline water under the influence of gravity could easily be reversed by changes in the piezometric surface induced by pumpage. Detailed study of the encroachment of this saline water into Galesville fresh-water sources is needed for specific local conditions.

Besides the flow described above in the northern part of the area studied, another flow in the Mt. Simon Aquifer is indicated in the southern part of the area (fig. 13). Sizable flow vectors are shown southward toward Louden and on to St. Jacob, Salem, Clay City, and Dale. Possibly Mt. Simon water flows to the Rough Creek Fault Zone (fig. 16) and then upward through the faults and fractures in that area. If so, important inferences about oil accumulation can be drawn. For one thing, filtration of finely dispersed hydrocarbons from the moving water may have resulted in commercial accumulations of oil. Furthermore, in accordance with the principles laid down by Hubbert (1953), any oil deposits that may exist in the Mt. Simon should be displaced.

The indications of flow through the Mt. Simon Aquifer in the deep part of the Illinois Basin are based on data having questionable validity. Data are available for only a few locations, and the values for $H^{1.00}$ are deduced from drill-stem test results. If the DST results are in error by as much as two or three percent, the indicated flow directions may be changed. Such an error is not likely, but it is a possibility. Also, the flows in figure 13 were calculated on the assumption that the density of the interstitial water varies linearly with depth and with

distance. If the density actually increases more rapidly than this with depth, the forces available for flow are greater than indicated; on the other hand, if the density increases less rapidly, the force is less than indicated. Furthermore, some question exists about the water densities that should be used in the calculations. The value given for Salem, 1.165, appears reliable. No density data were available for Louden and Clay City; therefore, the Salem value, 1.165, was assumed. No Mt. Simon Sandstone Formation was present in the Cuppy well at Dale; the water samples from the St. Peter, Potosi, and Eau Claire in this well all had relative densities of approximately 1.13; therefore this value was used in the calculations for figure 13. The absolute values of Ψ_{ρ_i} change as different values are assumed for ρ_i. However, the indicated flow direction, north to south, can be reversed only by the assumption of unreasonably small values for the densities of the interstitial waters; therefore, the uncertainty about water densities does not seriously affect our conclusions about the direction of flow.

In the deeper part of the Illinois Basin, data for $H^{1.00}$ in the Mt. Simon Aquifer are available only for Salem, Louden, and St. Jacob. Eau Claire data are available for Dale, while Shakopee (Knox) data are available for Clay City. All of these data were used in making the calculations for figure 13. This procedure is valid if we can assume that the Mt. Simon, Eau Claire, and Knox are hydraulically connected in this area; however, we have no assurance that they are connected.

When Potosi (Knox) data from the Dale well were used instead of Eau Claire data, the results of the calculations indicated essentially no flow from Salem and Clay City toward Dale. Thus, our conclusions about flow in this area are uncertain. On the whole, though, most of the data indicate southerly flow in the deeper rocks in the southern part of Illinois.

The calculated values of ($\Psi_{\rho_{ave.}}/s$) in the southern part of the state are in general considerably larger than in the northern part. This is to be expected since the permeability of the Mt. Simon Aquifer decreases as we go southward. Other things being equal, in order to cause the flow of a given volume of water, a rock having low permeability requires a greater value of ($\Psi_{\rho_{ave.}}/s$) than does a rock having high permeability.

Cartwright (1970) found, from temperature measurements, indications that water is flowing upward in the area of the Rough Creek Fault Zone. This conclusion is consistent with the conclusions presented above about the likelihood of southward flow in the deeper part of the Illinois Basin.

Possible anomalies in head exist at Ancona, at the South well, and at Newport. As far as Ancona is concerned, all of the indicated flow directions except one point toward Ancona (fig. 13). However, some of the values of $\Psi_{\rho_{ave.}}/s$ may not be large enough to be significant. Conditions at Ancona and at the South well will be discussed later, in the section dealing with flow in the Ironton-Galesville (p. 37).

As far as Newport is concerned, all of the indicated flow directions point outward. At Newport $H^{1.00}$ is about 300 feet greater than at observation points to the west in Illinois. About 100 to 200 feet of this head difference can be accounted for by the differences in elevation (1,000-1,500 feet) between the observation point at Newport and those to the west of Newport. Thus, a 1,000-foot interval containing water having an average density of 1.10 would result in a difference in $H^{1.00}$ equal to 1,000 x 0.10, or 100 feet. The remainder of the

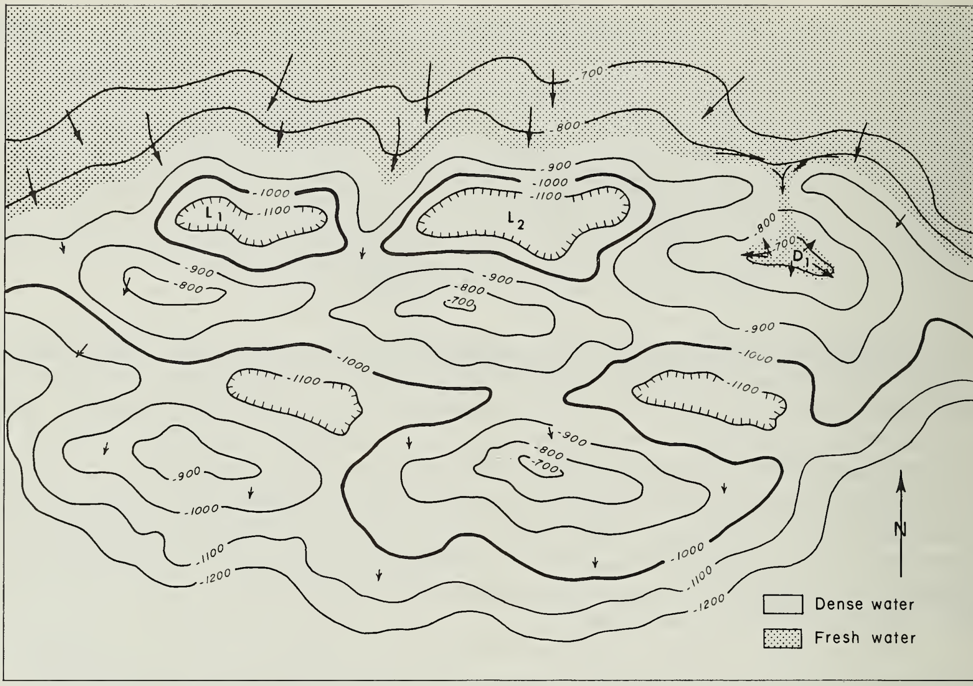
difference between $H^{1.00}$ for Newport and for the Illinois points (100 to 200 feet) should be available to cause flow away from Newport, unless, of course, it is diminished by the effects of intervening troughs. The high value of $H^{1.00}$ at Newport is probably the net result of two factors: (a) The ground elevation along the Cincinnati Arch is about 300 feet higher than at Newport; presumably some of the head in the outcropping Ordovician rocks along the arch is transmitted to the Cambrian Mt. Simon Aquifer. (b) The Mt. Simon rises more than 3,000 feet in going from Newport to the arch (fig. 17); a 3,000-foot column of dense water (ρ = 1.05 to 1.10) would add 150 to 300 feet to the head.

Possible explanation for random flow directions in the Mt. Simon Aquifer.— Locally the indicated flow directions in the Mt. Simon vary in almost a random fashion (figs. 13 and 14). Some of the apparent variation in flow direction may be due to errors in the data used. But this is not a likely explanation for all of the variation, because the water-level measurements, water sampling, and analysis are generally made with considerable care. In particular, in a given reservoir the data from well to well are consistent with respect to base elevation. The reported gradients usually are based on observations in about a dozen wells. The observed gradients appear to result from real differences in the heads that exist in various parts of the reservoir.

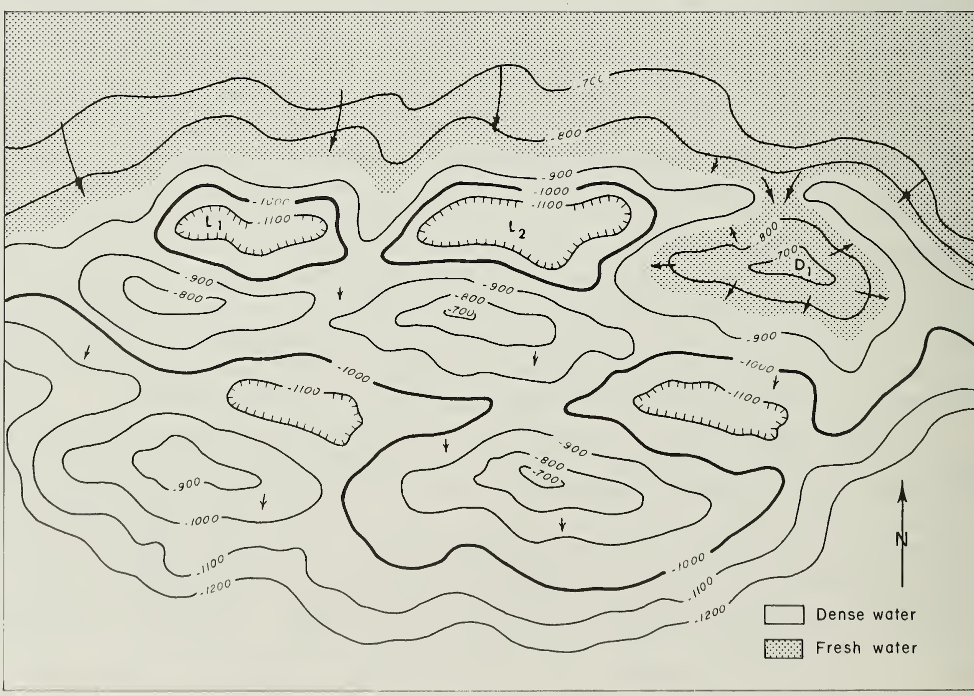
How, then, are the random directions of apparent flow to be explained? As indicated above, in an aquifer, like the Mt. Simon Aquifer, that contains stratified water of variable density, flow is a complex function of water density, hydraulic head, permeability, and structure. By way of illustration, a hypothetical case has been set up to show flow patterns that can occur when fresh water encroaches into an aquifer that is initially saturated with dense saline water (fig. 18). Obviously the direction of flow in one part of the aquifer can be at right angles to the direction of flow in another part of the aquifer; in certain parts the flows can even be in opposite directions. Furthermore, the direction of flow can change as the displacement process continues. For example, early in the process, light, relatively fresh water will generally flow around "lows" in the roof of the aquifer. Later, as the interface between light and heavy water is displaced downward, water can flow under these "lows." Of course, similar effects can occur, in reverse, as dense water displaces a lighter water.

To prove that this kind of flow is occurring in any given aquifer would require far more data than are available. The effects illustrated in figure 18 do appear to give a reasonable mechanism for explaining the variation in apparent flow direction that is observed in the Mt. Simon in the Illinois Basin.

Other possibilities also should be kept in mind. In some parts of the aquifer the observed differences in head may be just enough to balance heavy water on the side of a trough or in a series of troughs; or the differences in head may balance relatively heavy water under a dome or across a saddle, leaving no excess head to cause flow, as pointed out previously (p. 17). That is, differences in head can exist even though the water is not flowing. Perhaps some of the gradients that have been deduced for the Mt. Simon (figs. 13 and 14) mirror such static situations. Here, again, proof would require much more data, but the possibility appears reasonable.

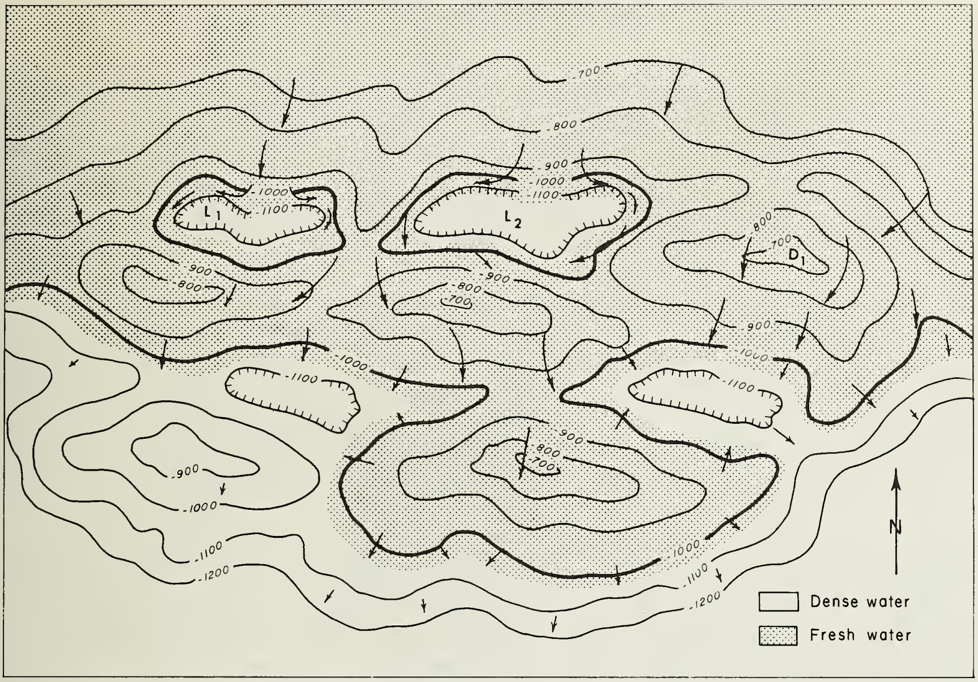


A - Part of hypothetical basin. In the north, fresh water invades shallower part of basin. Fresh water reaches spill point of dome D_1 and starts to displace dense water from dome. Note opposite directions of flow of fresh water near spill point.

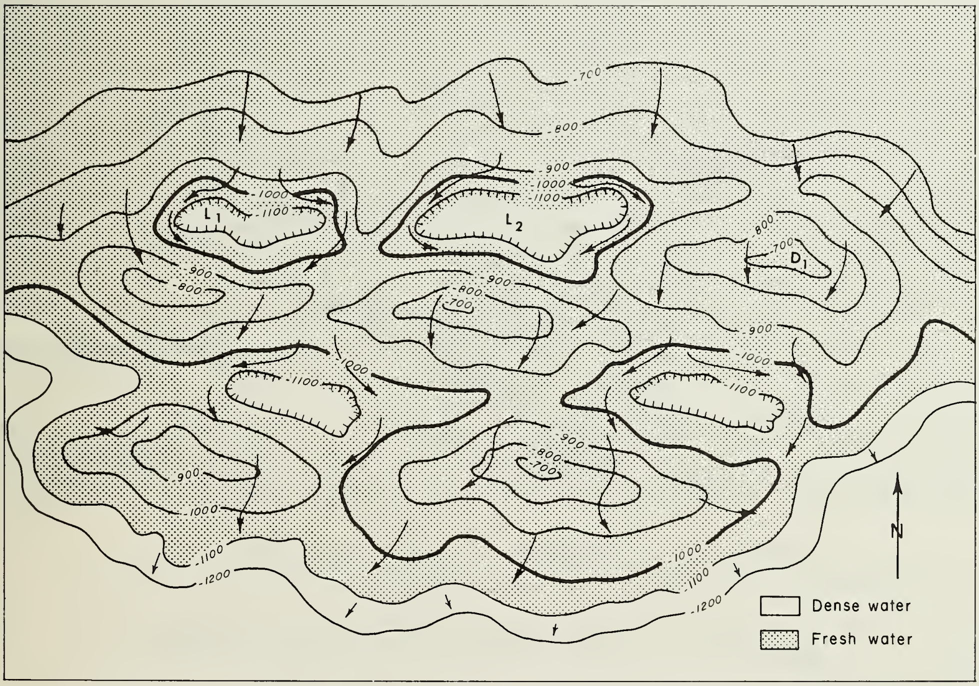


B - Second stage of invasion. Fresh water displaces dense water in dome D_1. Note opposite directions of flow in east and west ends of dome.

Fig. 17 - Displacement of dense water



C – Invading fresh water flows around lows L_1 and L_2. Note opposite directions of flow along periphery of lows L_1 and L_2.



D – Advanced stage in displacement process. Note lows under which little or no flow occurs.

by fresh water in a hypothetical aquifer.

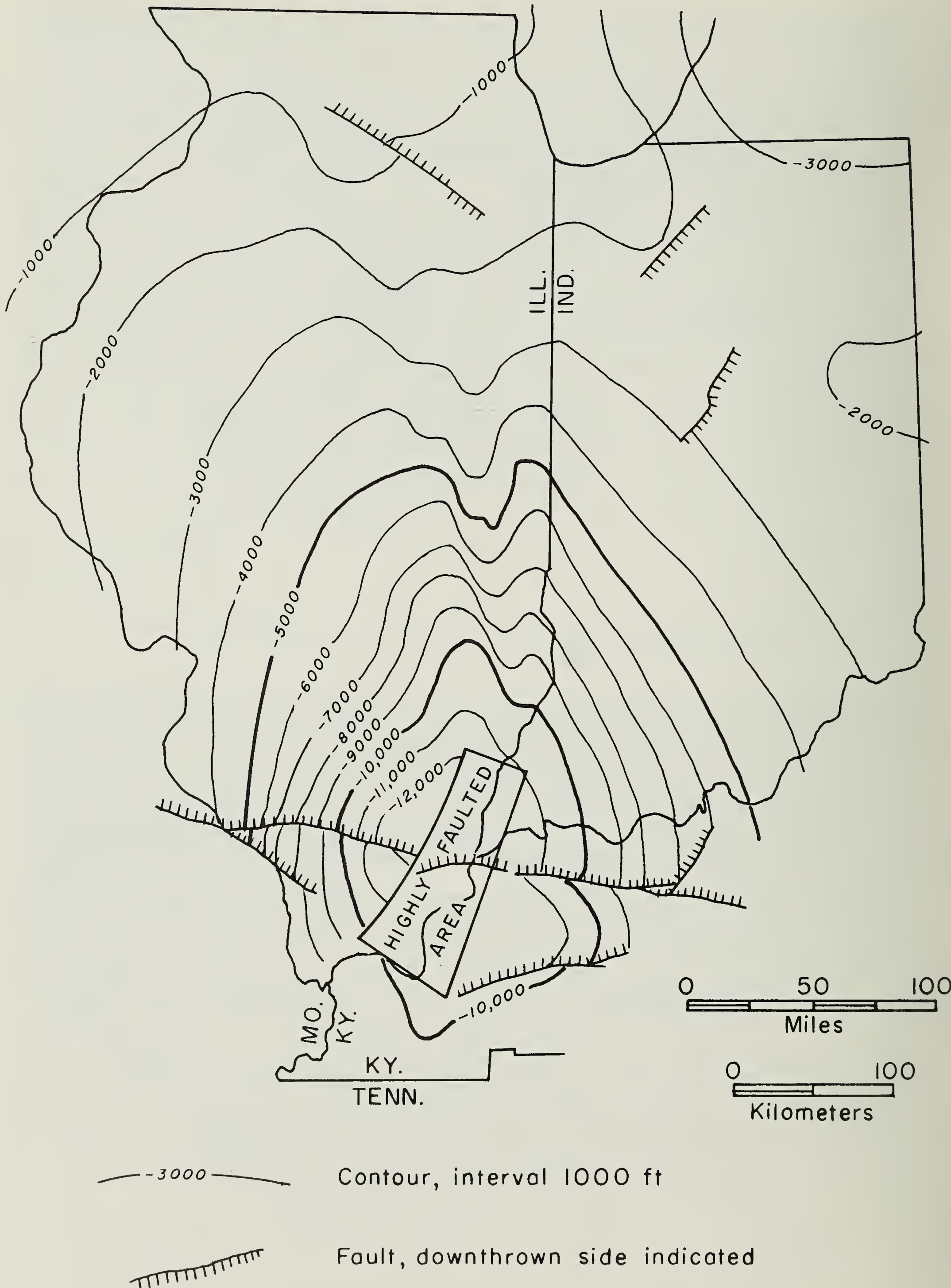


Fig. 18 - Structure on top of Mt. Simon Formation (prepared by T. C. Buschbach and T. L. Chamberlin).

Flow in the Ironton-Galesville and St. Peter Aquifers

The data in table 2 on $H^{1.00}$ and ρ for the Ironton-Galesville were subjected to the same treatment as described above for data from the Mt. Simon Aquifer (fig. 19). Density data were not available for water from the Ironton-Galesville at Lake of the Woods; therefore, the density of Ironton-Galesville water at Royal Center was used in the calculations for the interval between Lake of the Woods and Royal Center. Likewise, the density of Crescent City water was used in the calculations for the interval between Lake of the Woods and Crescent City.

In a general way, flow is indicated from the north and the northwest toward the central and western parts of Illinois. However, a number of anomalous situations appear in figure 19. A small flow is indicated from Shanghai toward Ancona, while the other data generally indicate flow toward Shanghai. In figure 19, on lines showing flow between Ancona and other points, all arrows, except the one from Herscher, point toward Ancona; therefore, a potential sink (an area of low head) may exist in the Ironton-Galesville in the vicinity of Ancona.

In some ways, figure 19, showing flow in the Ironton-Galesville, resembles figure 13, showing flow in the Mt. Simon Aquifer, in the Ancona area. In figure 13 all arrows, with the exception of the one toward the South well, also point toward Ancona; the value of the gradient toward South may not be significant. Perhaps a sink exists in the Mt. Simon also in the vincinity of Ancona. Since the Mt. Simon rests on granite, such a condition can exist only if water is flowing upward from the Mt. Simon to the Ironton-Galesville, displacing water from the Ironton-Galesville into overlying aquifers. A net head difference of about 120 to 140 feet exists between the Mt. Simon and the Ironton-Galesville, indicating lack of communication between the two aquifers. However, salinity data indicate that Mt. Simon water may be flowing upward to the Ironton-Galesville in the Ancona area. In the southeast dome of the Ancona reservoir the Ironton-Galesville water contains 3,800 mg/l of total dissolved solids (TDS), while in the northwest dome it contains 6,700 mg/l. These values can be compared with those in surrounding reservoirs: Troy Grove - 720 mg/l, Herscher - 2,528 mg/l, Pontiac - 1,300 mg/l, Lake Bloomington - 1,955 mg/l. On the basis of its depth and location, the Ironton-Galesville water at Ancona would be expected to contain only about 1,200 mg/l TDS. Thus, the Ancona Ironton-Galesville water contains three to five times the dissolved solids that would be expected; furthermore, the solids content is about one-fifth to one-third of that of the Mt. Simon. Perhaps Mt. Simon water, flowing upward through the Eau Claire to the Ironton-Galesville, has mixed with the native Ironton-Galesville water to give the observed salinities. Willman et al. (1942, p. 285) suggest that the presence of salty water in some wells in central La Salle County is the result of the introduction of water from the Mt. Simon into higher fresh-water aquifers through joints in the intervening strata.

The data in figure 13 and figure 19 and the information about water salinities can be explained if we assume that one or more faults in the general vicinity of Ancona permit vertical flow from the Mt. Simon Aquifer upward to the Ironton-Galesville and higher aquifers. Faults are known to exist at Troy Grove; although these faults do not permit flow from the Mt. Simon to the Ironton-Galesville, they do permit flow between the Mt. Simon and zones in the Eau Claire

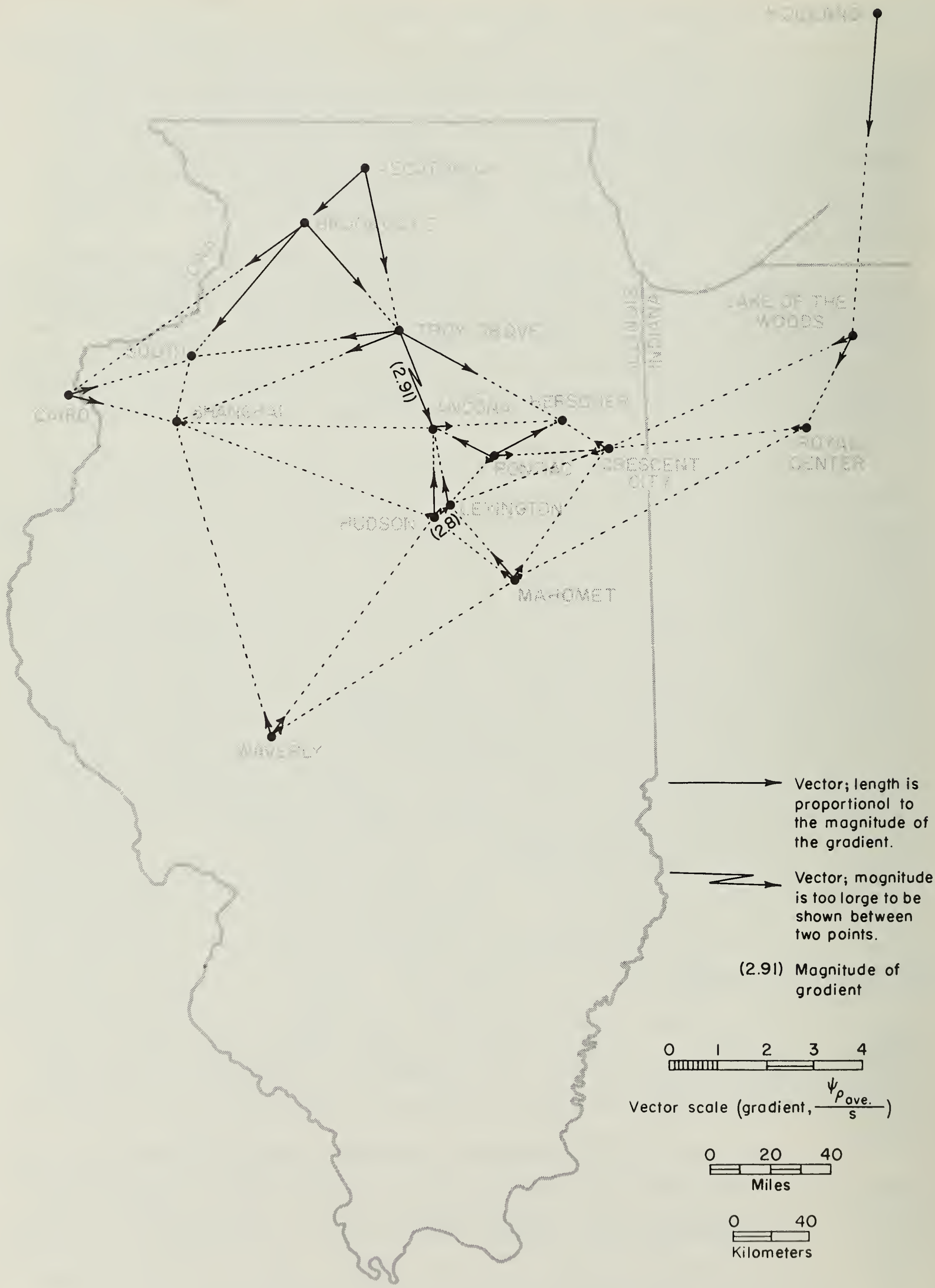


Fig. 19 - ($\psi_{\rho\,ave.}$)/s for pairs of points in the Ironton-Galesville. Arrows indicate general direction of flow. Length of arrows is proportional to net force available to cause flow. (Data for Holland are for the Franconia.)

(Buschbach and Bond, 1967, p. 49). It is reasonable to expect faults of this kind to exist also at other places, like Ancona, along the La Salle Anticlinal Belt. A fault of this kind, if it does exist, probably is located east of Ancona, since the local gradient in the Mt. Simon Aquifer at Ancona points toward the east.

What has been said above about Ancona applies also, in some degree, to the area around Shanghai and the South well. The data for that area could be explained by the assumption that a fault exists that permits some upward flow but not enough flow to equalize the heads in the Mt. Simon and the Ironton-Galesville.

The data plotted in figure 19 represent only the information that was uncovered incidental to the study of relatively heavy brines. Much more information about the Ironton-Galesville, especially where it contains fresh water, is available. Since water from the Ironton-Galesville is used locally in many parts of the state, it is not surprising that data from relatively few points should present the confusing pattern shown in figure 19. Probably a detailed study of data from fresh-water wells would resolve some of the apparent anomalies.

Values of $H^{1.00}$ for the St. Peter are given in table 3. Here, as for the Ironton-Galesville, only the data uncovered incidental to the study of heavy brines are tabulated. Much more data are available for fresh-water wells that produce from the St. Peter.

For the northern half of Illinois, the data in table 3 indicate no broad general pattern of flow in the St. Peter. Water is withdrawn from the St. Peter locally at many places in northern Illinois. Because of the sparsity of data presented here, the effects of local withdrawals are not revealed.

In the southern part of Illinois, data on water density, water levels, and formation pressures for the St. Peter, Ironton-Galesville, and intervening formations are sparse. In figure 20 all of the available water-density data for these formations are plotted against subsea depth; data from Meents et al. (1952), listed in table 4 (app. 2), are also included. If the assumption is made that these strata are connected hydraulically, which is questionable, the density data indicate that these rocks have been flushed by relatively fresh water flowing generally toward the south and east. In figure 21, which presents data for both ρ and Z, the S-shaped line marks a fairly sharp boundary between what may be paleobrines, in the southeastern part of the Illinois Basin, and the less dense invading waters from the northwest. To the north and west of this S-shaped line the density of the formation waters, for a given subsea depth, is considerably less than the density at the same depth southeast of the line.

The S-shaped line of demarcation between dense and light waters in the interval from the St. Peter to the Ironton-Galesville (fig. 21) is similar to the isocons for St. Peter waters given by Meents et al. (1952, fig. 13). It also resembles the curves that were deduced from the hypersurface that was fitted to the $\rho*(x, y, z)$ data for the Mt. Simon Aquifer (fig. 11). Perhaps the heavy waters in all of these deep aquifers are banked up against the north and west sides of troughs in the La Salle and Clay City Anticlinal Belts (fig. 16).

The water-density data indicate that fresh water has flowed into the interval from the St. Peter to the Ironton-Galesville from the northwest toward the southeast; however, with the density data alone one cannot establish whether or not the water is still flowing. To do this would require accurate data for $H^{1.00}$ also; such data are not available for this interval in the southern part of the Illinois

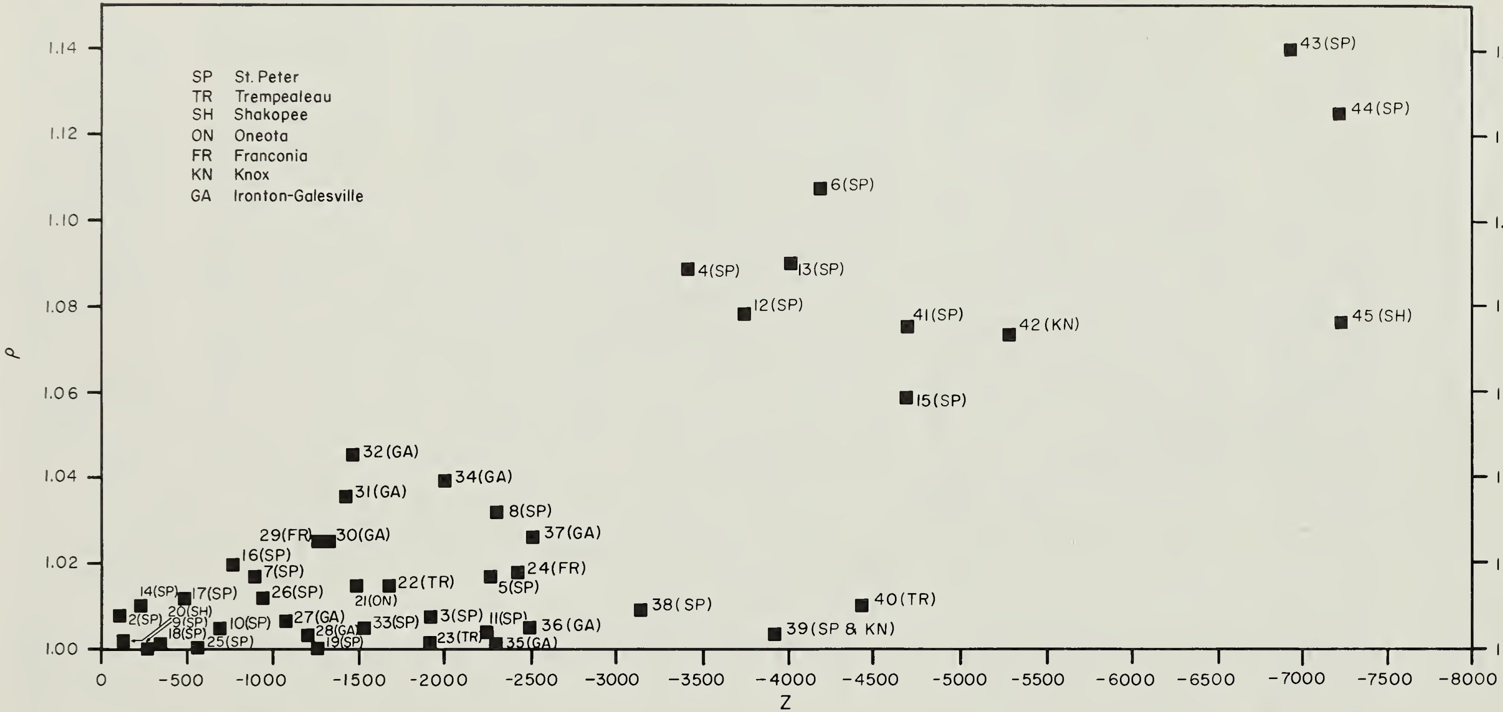


Fig. 20 - Relation between ρ and Z for waters from the St. Peter through the Ironton-Galesville in the Illinois Basin. Numbers 2-24 represent data from Meents et al., 1952; these numbers correspond to numbers given in table 4 of present report. Numbers 25-45 represent data from tables 2 and 3 of present report.

25 - Crescent City
26 - Tuscola
27 - Herscher
28 - Gary
29 - Royal Center
30 - Royal Center
31 - Roayl Center

32 - Royal Center
33 - Lamb
34 - Crescent City
35 - Lake Bloomington
36 - Hudson
37 - Mahomet
38 - Brohammer

39 - Louden
40 - Tuscola
41 - Salem
42 - Pickel
43 - Ford
44 - Dale
45 - Clay City

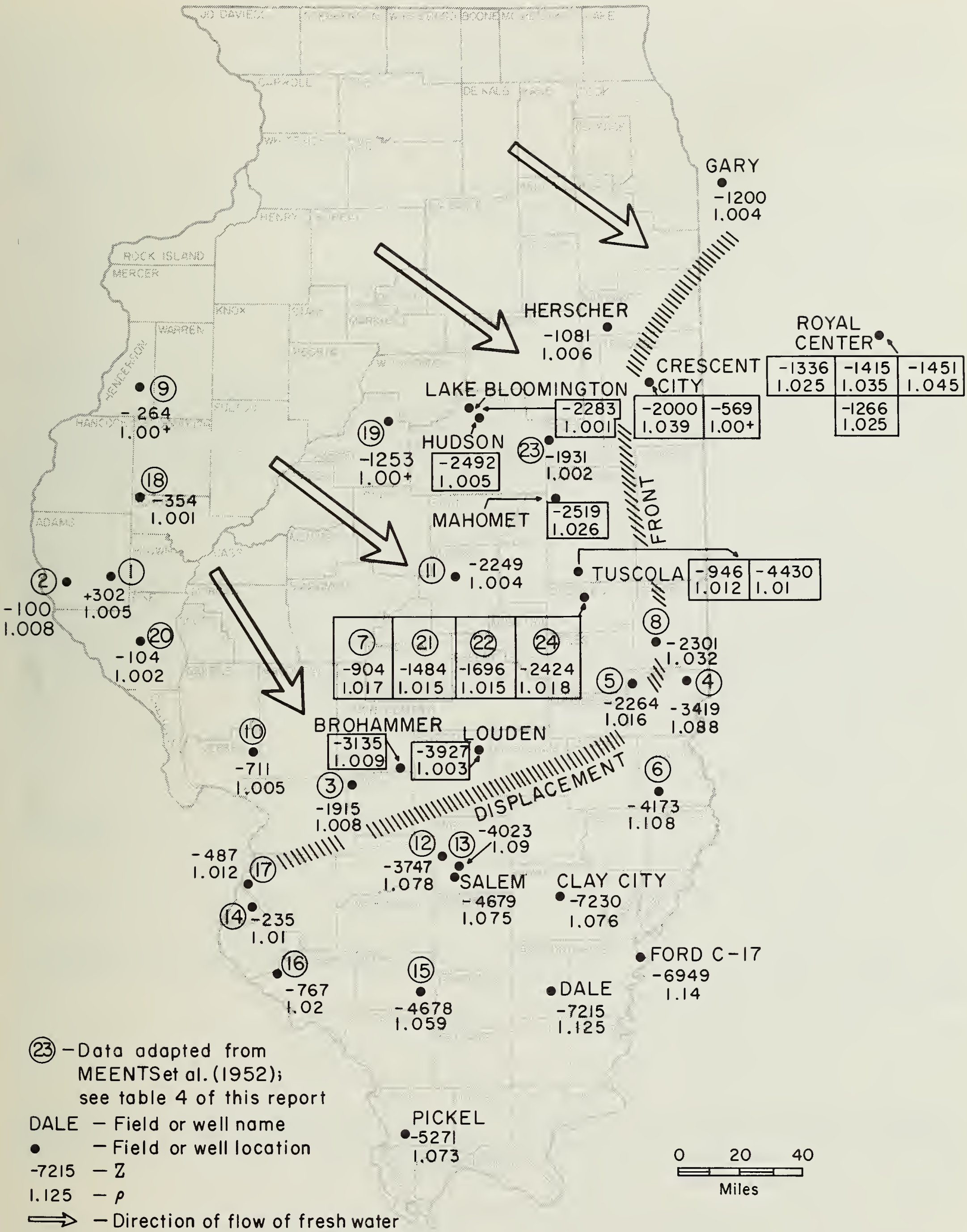


Fig. 21 - Flushing of brine by fresh water, as indicated by variation of ρ at corresponding values of Z, St. Peter through Ironton-Galesville.

Basin. However, Cartwright (1970), on the basis of temperature measurements, concluded that water is now flowing upward in the southeastern part of the basin. Possibly water is still flowing toward the southeast in the interval from the St. Peter to the Ironton-Galesville.

Vertical Flow

(a) Vertical flow from the Mt. Simon Aquifer to the St. Peter. — The values of $H^{1.00}$ calculated for the Mt. Simon are generally greater than the values of $H^{1.00}$ for the St. Peter (tables 1 and 3).

Bond and Cartwright (1970, p. 1496) show that if a conduit for flow exists, water flows upward from one aquifer to another if

$$(H_2^{1.00} - H_1^{1.00}) > (\rho_2 - 1.00)\,\Delta Z_c.$$

Here $H_2^{1.00}$ is the fresh-water head at the top of the lower aquifer, $H_1^{1.00}$ is the fresh-water head at the bottom of the upper aquifer, ρ_2 is the density of the water in the lower aquifer, relative to fresh water, and ΔZ_c is the vertical thickness of the intervening cap rock. Table 5 (app. 2) gives the results of calculations of

$$\left[H^{1.00}_{Mt.S.} - H^{1.00}_{St.P.}\right] \quad \text{and} \quad \left[(\rho_{Mt.S.} - 1)\,\Delta Z_c\right]$$

for ten locations in the Illinois Basin for which data are available. The calculations show that water should flow upward from the Mt. Simon to the St. Peter at points from Shanghai and Ancona in the north to about Louden in Fayette County. At St. Jacob and Salem, in Madison and Marion Counties, respectively, the difference in $H^{1.00}$ is not great enough to cause upward flow.

Water can flow downward if

$$\left[H_2^{1.00} - H_1^{1.00}\right] < (\rho_1 - 1)\,\Delta Z_c.$$

Here ρ_1 is the relative density of the water in the upper aquifer, in this case the St. Peter. Calculation shows that at Salem

$$\left[H^{1.00}_{Mt.S.} - H^{1.00}_{St.P.}\right] \text{ is not less than } (\rho_{St.P.} - 1)\,\Delta Z_c,$$

but is 148 greater (table 5). Therefore, at Salem water cannot flow downward from the St. Peter to the Mt. Simon either.

Bond and Cartwright (1970, p. 1496) show that if

$$(\rho_1 - 1)\,\Delta Z_c < (H_2^{1.00} - H_1^{1.00}) < (\rho_2 - 1)\,\Delta Z_c,$$

a static interface exists between the two waters in the rock between the two aquifers. The distance from the bottom of the cap rock (i.e., top of the lower aquifer) to the equilibrium interface, $\Delta Z_{eq.}$, is given by

$$\Delta Z_{eq.} = \left[H_2^{1.00} - H_1^{1.00} - (\rho_1 - 1)\,\Delta Z_c\right] \Big/ (\rho_2 - \rho_1).$$

Application of this equation to the data from the Johnson well at Salem shows that the equilibrium interface in a conduit between the Mt. Simon Aquifer and the St. Peter should be about 1,640 feet above the top of the Mt. Simon.

The preceding discussion presents an overly simplified picture of the potential for vertical flow. It ignores the presence of other porous zones, in the Ironton-Galesville and the Knox, for example. These zones could have hydraulic heads greater than those in the Mt. Simon or less than those in the St. Peter, but this is not likely. If the head in these intervening beds lies between the heads for the Mt. Simon and the St. Peter, our conclusions about vertical flow should hold, qualitatively.

(b) Vertical flow from the Mt. Simon Aquifer to the Ironton-Galesville. — The values of

$$\left[H^{1.00}_{Mt.S} - H^{1.00}_{Glsvl.} - (\rho_{Mt.S.} - 1)\,\Delta Z_c\right]$$

are given in table 6 (app.2) for those locations for which Mt. Simon and Ironton-Galesville data are available.

At Pecatonica and at Brookville a natural difference in head of about 30 feet will force Ironton-Galesville water down to the Mt. Simon if any conduit for flow exists. At Royal Center, as noted before, the difference between the head in the Mt. Simon Aquifer and that in the Ironton-Galesville is just enough to lift Mt. Simon water up to the Ironton-Galesville. At most locations in northern Illinois, a residual force equivalent to about 100 to 175 feet of fresh-water head is available to cause flow from the Mt. Simon up to the Ironton-Galesville.

Most of the measurements reported here were made in the past twenty years. Especially in the Ironton-Galesville and the St. Peter, they reflect the effects of pumpage in modern times. As noted previously, Suter et al. (1959) have shown that in northeastern Illinois the head in the Cambrian-Ordovician Aquifer, of which the Ironton-Galesville and the St. Peter are a part, has been lowered considerably as a result of this pumpage. In 1898 the static water level in the St. Peter at Tuscola was about 150 feet above its present level (Habermeyer, 1925). Before withdrawal of water was begun, the heads in the Mt. Simon and in the overlying aquifers were probably nearly balanced, with little net force available for vertical flow.

Measurements of the head of water in wells drilled into porous zones above and below a cap rock have been used to indicate whether or not the cap rock may leak (Bays, 1964). The assumption is made that if an avenue for leakage exists, the head in the two zones must become equal over geologic time. Therefore, if a difference in head is observed, the conclusion is reached that the cap rock is tight. This conclusion may be valid if the difference in head across the cap rock has existed for a long time. But if the difference in head has existed for only a relatively short time, the flow of water through any faults and fractures in the cap rock may not have been sufficient to equalize the heads above and below the cap rock. Therefore, conduits for flow may exist even if a head difference is observed, if this head difference has developed recently as a result of pumpage, as appears likely in the deeper aquifers of northern Illinois.

(c) Vertical flow from the Ironton-Galesville to the St. Peter. — Data for both the Ironton-Galesville and the St. Peter are available for only a few locations (table 7, app. 2). The data indicate that in most of northern Illinois little or no difference in head exists to cause flow between these two aquifers. At Pecatonica water would flow downward through any conduit from the St. Peter to the Ironton-Galesville, under the influence of a head

difference of about 20 feet. At Crescent City water would also flow downward, under a head of about 25 feet; because of the high density of the Ironton-Galesville water, more than 80 feet of head would be required to force Ironton-Galesville water up into the St. Peter.

The results of the above calculations with respect to vertical flow between the Mt. Simon, the Ironton-Galesville, and the St. Peter are mapped in figure 22.

Origin of Illinois Basin Brines

Bredehoeft et al. (1963), Clayton et al. (1966), and Graf et al. (1965, 1966) have discussed mechanisms for the concentration of sea water that might explain the origin of the highly saline brines found in the deep part of the Illinois Basin. They concluded that the water in the deep aquifers in the basin is flowing and that some of the water is being discharged upward through clay shales that act as osmotic membranes.

The present study indicates that in recent times, prior to pumpage, the vertical head differences in the deeper rocks of the Illinois Basin were scarcely large enough to cause upward flow through an open conduit, let alone through a very tight shale that might filter out dissolved salts (fig. 22). If any water now flows upward, say from the Mt. Simon to porous formations such as the Ironton-Galesville and the St. Peter in the central part of the basin, most likely it flows through fractures in the tight intervening strata.

SOME CONCLUSIONS ABOUT SYSTEMS CONTAINING WATER OF VARIABLE DENSITY

Oil and Gas Accumulation

Hydrodynamic potential values, deduced from pressure readings and water-level observations, have been used in attacking a number of problems related to oil and gas accumulation. These problems are encountered in the study of tilted oil-water interfaces, hydrodynamic sinks, and long-distance flow through aquifers. Conclusions from some of these studies may need modification when the effects of variable water density in inhomogeneous strata, discussed above, are taken into consideration. Some of these effects are discussed in the following paragraphs.

Tilted Oil-Water Interface

Hubbert (1953) discusses some of the implications of potential gradients with respect to flow in aquifers in which oil or gas reservoirs exist. In particular, he shows that in an aquifer whose water is constant in composition: (1) A sloping potentiometric surface is always accompanied by flow (p. 1974), and (2) a sloping potentiometric surface causes a tilting of the interface between the water and an oil or gas deposit in a reservoir (p. 1988).

Later, in a general discussion of tilted oil-water interfaces (p. 2023), Hubbert concludes:

> The only way, therefore, that a tilted oil-water interface can be sustained indefinitely except by a dynamic groundwater environment is for the oil to be restrained by some kind of impervious seal, such as an asphalt stratum.

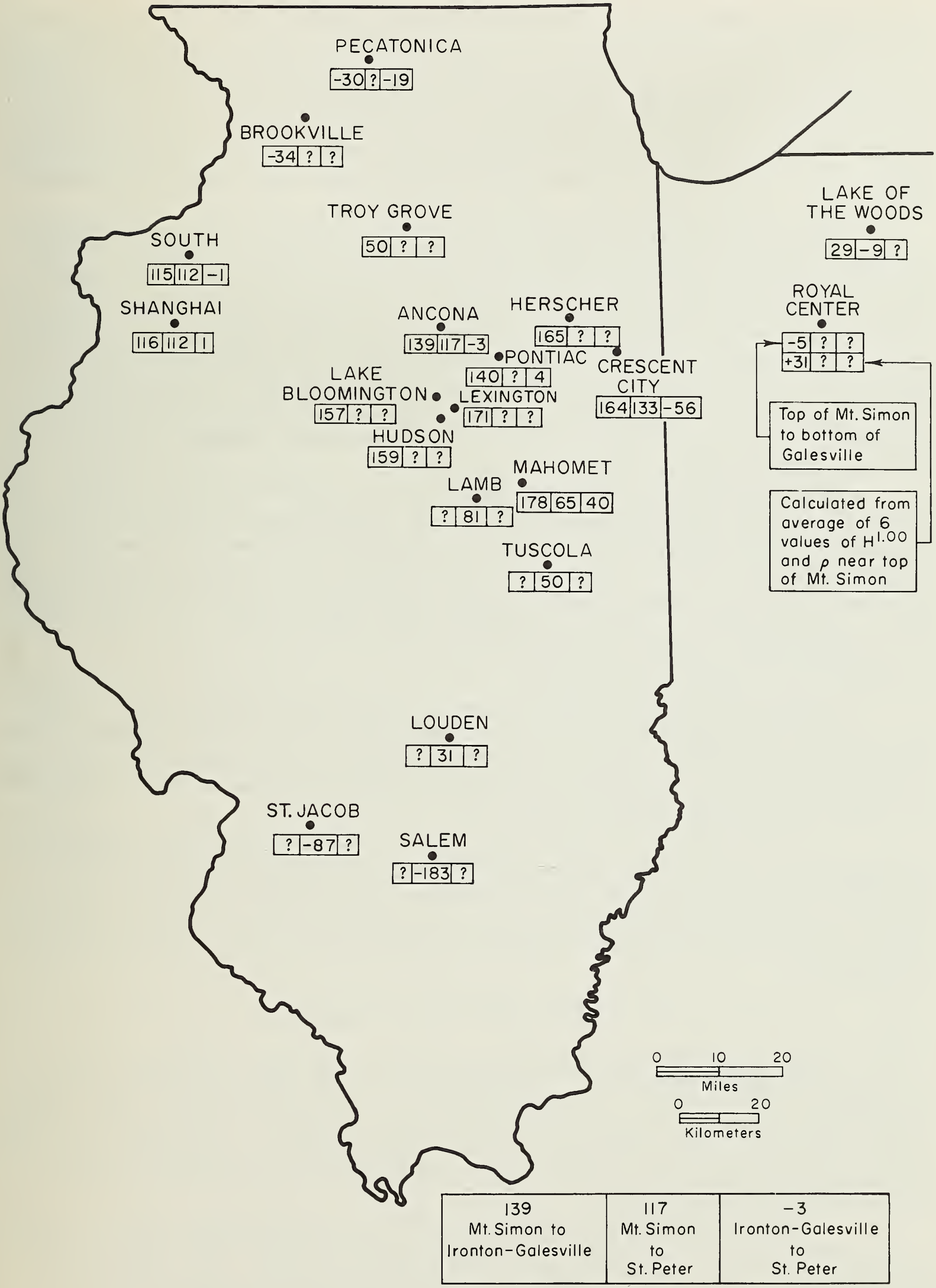


Fig. 22 - Head, $[\Delta H^{1.00} - (\rho_2 - 1)\,\Delta Z]$, available to cause upward flow. Negative value indicates head insufficient to cause upward flow. ρ_2 = relative density of water in lower aquifer.

This conclusion appears to be valid, if the density of the water below and around the oil deposit is constant. But if the density of the water varies and if the aquifer rock is anisotropic and contains troughs and "corrugated" flow paths, a gradient in head or in potential can be maintained indefinitely without flow. Such a gradient will cause a tilt in the oil-water interface just like the tilt that accompanies a gradient that is caused by flow. Furthermore, in such a variable-density aquifer, this tilt may be maintained indefinitely without any flushing by invading waters.

Thus far, no definite evidence is known for the existence of such oil reservoirs, that is, reservoirs with tilted oil-water interfaces caused by stratified waters of variable density that are not flowing. But many reservoirs are known in which variations exist in the elevation of the oil-water contact throughout the field; at least some of these variations may be the result of the density effects described above. Many Illinois oil deposits are found off the tops of structures. Often the reason given is that the best porosity is off structure; in some cases a better explanation might be that the head differences caused by stratified waters in an inhomogeneous reservoir rock have resulted in the displacement of the oil deposit.

Uniform reservoir rocks should not contain such anomalous deposits. Likewise, aquifers filled with water of constant composition and density should not contain these anomalous oil deposits. But any oil-bearing strata having irregular flow paths (i.e., strata with cross-bedding, channeling, and pinchouts) and containing water whose density varies could have reservoirs with tilted oil-water interfaces or deposits located off the tops of structures.

Long-Distance Flow Through Aquifers

A number of researchers have used measurements of potential or of head to prove that water has flowed through aquifers for a considerable distance. For example, Hitchon (1969a and b), as a result of such a study, concluded that water is flowing from the foothills in western Alberta eastward to the Ft. McMurray tar sands area through various aquifers.

In view of what has been said about the effects of stratified dense waters in troughs, we need to consider the possibility that some of the potential differences observed in such studies may not be caused by flow. In some instances the observed potential differences may simply represent the hydraulic head required to balance static layers of relatively dense water on the sides of a series of troughs.

Underground Waste Disposal

Deep wells are often used for the disposal of liquid industrial wastes (Bergstrom, 1968; Warner, 1965; Ives and Eddy, 1968). Since these liquid wastes contain high concentrations of dissolved materials, they often have high densities relative to fresh water. Obviously the principles outlined in other sections of this report will have application to problems connected with the underground flow of these heavy waste solutions.

For example, suppose a pickle liquor from a steel plant, relative density 1.22, is injected near the bottom of an aquifer that contains water whose relative density is 1.10. In such a system no impermeable cap rock is needed to protect fresh water in higher aquifers. Unless the point of injection is at a

structural low, the pickle liquor will flow downward under the influence of gravity. Suppose that the bottom of the aquifer dips, say 40 feet per mile. The gravitational force available to cause flow will be equivalent to a head of 40 x (1.22-1.10), or 4.8 feet per mile. From this head and the porosity and permeability of the rock, the rate of advance of the injected liquid can be calculated. The rate of movement under the influence of gravity will be quite small, in most cases of the order of inches per year.

On the other hand, suppose that a light, toxic waste liquid, having a relative density of approximately 1.00, is injected into an aquifer at a point 1,000 feet below the contact between a brine having a relative density of 1.10 and fresh water. The brine will not necessarily serve as a barrier against upward flow of the injected liquid. As a matter of fact, the injected liquid can be expected to flow upward under the influence of gravity. The force available to cause flow will be equivalent to a gradient of 0.10 foot of head per foot of vertical distance. The rate of upward movement can be estimated if the porosity and permeability of the aquifer rock are known. In certain cases, depending on the porosity and permeability of the rock and the thickness of the intervening layer of dense water, as well as the density of this water, flow rates can be high enough to cause contamination of the fresh water by the injected liquid within a reasonable period of time. In cases like this, a tight cap rock above the heavy-brine aquifer is an absolute necessity if upper fresh-water zones are to be protected against contamination. Of course, one possible solution to the problem would be to mix the toxic waste with a heavy brine to give a dense injection mixture that would settle rather than rise through the aquifer.

If the aquifer into which the waste is injected contains fresh water in its upper zones, we need to consider the possibility that pumpage of this fresh water may reduce the head enough to cause the injected solution to rise and pollute the fresh-water zones. If a heavy waste material is injected under a relatively light saline water, the saline water will act as a screen to prevent the heavier waste water from rising into the fresh-water zone. Long before the waste water can reach the fresh-water zone, the fresh water will be displaced by the rising saline water.

Of course, if waste liquid is injected into an aquifer under sufficiently high pressure, it can be forced up into a fresh-water zone if conduits for flow are present. Proper completion of the injection well, with suitable provision for monitoring, should prevent this, especially if the injection pressure is kept within reasonable limits. These limits can be chosen if one knows the densities of the liquids and the vertical intervals involved. For example, suppose that in the case outlined above, 1,000 feet of saline water ($\rho = 1.10$) lies between the fresh water and the injected waste ($\rho = 1.22$). Assume that a channel of communication exists from the point of injection up to the fresh-water zone; this channel might be the result of a poor cement job, or it might be due to fracturing of the rock around the well bore. In order to raise the injected waste liquid up to the fresh-water zone, a fresh-water head equal to 1,000 x (1.22-1.00), or 220 feet, would be required. If $H^{1.00}$, prior to injection, is the same in the fresh-water zone and at the point of injection, a pressure difference equivalent to a head of 220 feet can be tolerated without any possibility of forcing the waste liquid up into the fresh-water zone. That is, an injection pressure of 0.433 x 220, or 95 psi, in excess of the original pressure can be used without fear of raising the injected liquid up to the fresh-water zone. If $H^{1.00}$ is greater at the point of injection than it is in the fresh-water zone, which is the usual case, the pressure limit will be correspondingly lower.

Each underground disposal well presents a special problem. However, the examples mentioned should show that gravitational effects caused by differences between the density of the native interstitial water and the density of the injected liquid may need to be taken into account in the design of a disposal well.

SUMMARY

1. Brines in the deep aquifers of the Illinois Basin are highly stratified. Over a distance of about 120 miles, along a line from West Chicago to Tuscola, the density of the interstitial water in the Mt. Simon Aquifer is approximately a linear function of subsea depth. To the west of this line the density is less, while to the east the density is greater, for a given elevation.

2. In the northern third of Illinois, water flows through the Mt. Simon Aquifer from the west to the east. In the northwestern part of Indiana, probably water flows from the Mt. Simon Aquifer up through faults and fractures to the Ironton-Galesville. This saline water from the Mt. Simon, flowing in a southwesterly direction in the Ironton-Galesville under the influence of gravity, appears to have penetrated at least as far as Crescent City.

3. Under present conditions, the indicated flow in the Mt. Simon Aquifer, up into the Ironton-Galesville, and down to Crescent City would have required about one million years.

4. In the deeper part of the basin, evidence exists that water in the Mt. Simon Aquifer is flowing southward, but some of this evidence is of questionable validity.

5. In some areas local flow directions in the Mt. Simon Aquifer vary in almost a random manner. The variation in flow direction may be caused by the complex nature of flow in such a stratified water system. As light water displaces heavier water in an aquifer, most of the flow occurs along the roof of the aquifer; therefore, local direction of flow is influenced greatly by the structure on the top of the aquifer. Saddles, domes, troughs, and corrugated flow paths affect the heads, and, therefore, the forces available to cause flow.

6. In the northern part of the Illinois Basin, some net head exists (about 100 to 200 feet) to cause vertical flow from the Mt. Simon Aquifer to shallower aquifers. Probably little or no effective head difference existed prior to modern pumpage from the shallower aquifers. In the deep aquifers that were studied, no evidence was found for abnormal heads that might have been caused by glaciation.

7. In an aquifer that contains stratified brines, a tilted oil-water interface can exist with zero flow in the water phase.

8. Principles of flow in variable-density aquifers have important applications in problems related to underground waste disposal.

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APPENDIX 1: CALCULATION OF $H^{1.00}$

I. Calculation of $H^{1.00}$ from Water-Level Observations

If a well contains fresh water, the observed virgin equilibrium water level in the well, with respect to sea level, is the value $H^{1.00}$ that we desire. If the well contains water whose density differs appreciably from that of fresh water, we must apply a correction to the observed water level in order to obtain $H^{1.00}$. If the water in the aquifer under consideration has the same density throughout, this correction is fairly straightforward. When the well has been swabbed or pumped until the composition of the produced water is constant, one can be reasonably certain that the hole is filled with water whose composition is constant throughout the depth of the hole and whose density is known.

On the other hand, if the water in the aquifer is stratified because its density varies with depth, the picture is not so simple. With a stratified system the composition of the produced water depends, in a complex way, upon the variation of water density with elevation, the horizontal and vertical permeability distribution within the rock, and the rate and duration of pumping. Even though the well is swabbed or pumped until the composition of the produced water is fairly constant, small variations in the density of the water column can introduce spurious effects. For example, if the water in 2,000 feet of the water column has a relative density differing from that of the rest of the column by 0.005, an uncertainty of 10 feet in head is introduced, depending upon which part of the column is available for analysis.

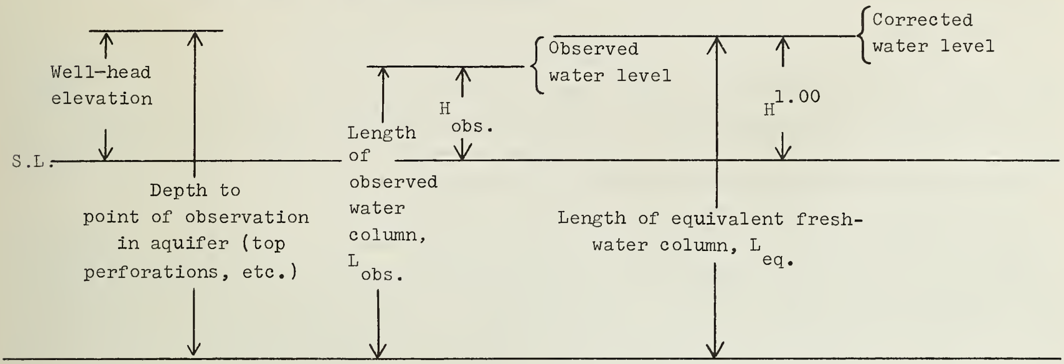
We should also note that for a stratified system, even if the water column in the well has a uniform density whose value is known accurately, the value $H^{1.00}$ that is calculated applies only for the topmost level in the well that is open to flow; generally this is at the top of the perforations. When a stratified aquifer is pumped, lighter water cones down into the perforated zone while heavier water cones upward to a lesser degree. Usually the density of the water in the hole below the top of the perforations is not known; therefore, we have no way of calculating $H^{1.00}$ for points below the top of the perforations. In cases where the density of the water in the aquifer is known accurately as a function of depth, we can calculate $H^{1.00}$ at various depths.

In a stratified system, then, we can determine $H^{1.00}$ for a single level in a given well. But in general we may not be able to determine, from water-level measurements, the head or the potential for other levels in the aquifer.

The following diagrams illustrate the treatment needed for correcting water-level observations to obtain $H^{1.00}$ for various cases:

A. Aquifer contains fresh water. Well is swabbed or pumped until produced water has relative density 1.00. No correction is needed.

B. Aquifer contains water having relative density ρ. Well is swabbed or pumped until produced water has relative density ρ.

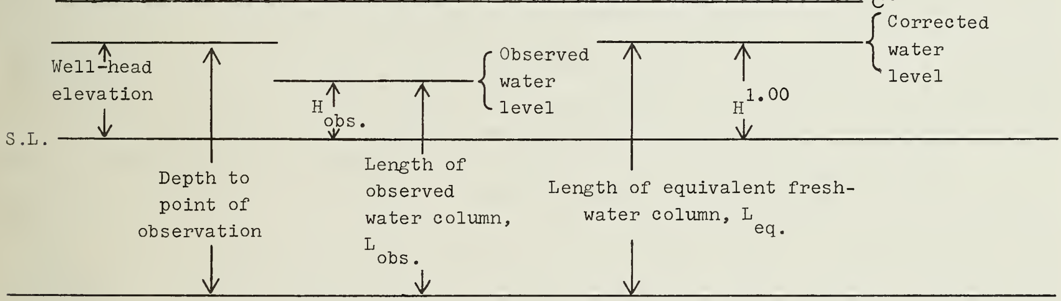


$$L_{eq.} = L_{obs.} \times \rho$$

$$H^{1.00} = H_{obs.} + L_{obs.} (\rho - 1)$$

This equation gives $H^{1.00}$ at the top of the perforations. At a depth ΔZ lower than this point, $H^{1.00}$ is larger by the amount $(\rho - 1) \Delta Z$.

C. Aquifer contains water whose density varies with depth. Well is swabbed or pumped until produced water has constant relative density ρ_c.



$$L_{eq.} = L_{obs.} \times \rho_c$$

$$H^{1.00} = H_{obs.} + L_{obs.} (\rho_c - 1)$$

This equation gives $H^{1.00}$ at the top of the perforations. In general, $H^{1.00}$ cannot be determined for other levels in the aquifer.

Even though the composition of the water column in the well is the same at various depths, the density will vary somewhat because of the increase in temperature with depth. No attempt was made here to correct for this temperature effect; thus small errors may be introduced in the absolute values calculated for $H^{1.00}$ for different drill holes. However, for a given depth, the temperature correction should be about the same for different wells; thus the fact that the temperature correction has been ignored should not appreciably change the relative values of $H^{1.00}$ in wells drilled to about the same depth. For wells having different depths, sample calculations were made on the assumption of reasonable values of the temperature gradient; these calculations indicated that

in the northern part of the state neglect of the temperature correction could introduce differences in $H^{1.00}$ of only a few feet at most. The uncertainties in the water-level data are probably considerably greater than any error that might be introduced by neglecting the temperature correction for the water column.

The water level in a well changes as the barometric pressure changes. The level is also affected by earth tides (Witherspoon et al., 1967, p. 2). Because of lack of information, no correction was made here for these effects. Since these barometric and tidal effects are usually about one foot or less, the error caused by neglecting them is not significant.

Analysts generally report specific gravity of the waters that they analyze. Often the base for the specific gravity determination is not specified. In this report, ρ , the water density relative to fresh water, was considered to be equal to the reported specific gravity. This procedure could result in small errors in the absolute value of ρ but should have little effect on the relative values of ρ over a reservoir where all samples were analyzed in the same manner.

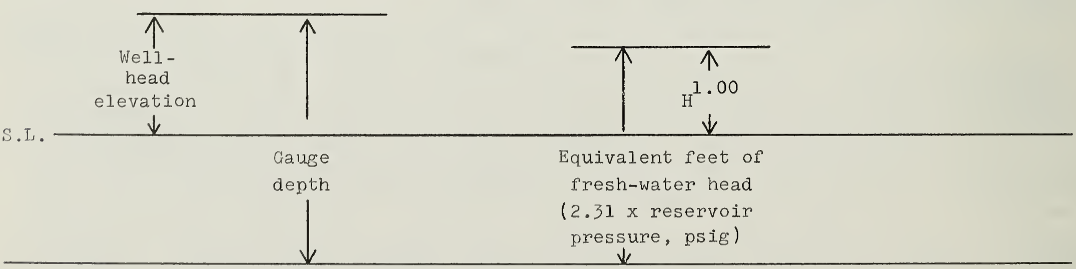
II. Calculation of $H^{1.00}$ from Drill-Stem Test Results

For many of the wells studied here, the complete service-company reports on drill-stem tests (DST) were available. In a few cases we had only the reports of pressures observed in the DST, usually the initial closed-in pressure (ICIP) and the final closed-in pressure (FCIP).

In order to determine $H^{1.00}$ from drill-stem results, one must know the reservoir pressure at one elevation in the aquifer. If ICIP and FCIP have the same value, this value is probably a good estimate of the reservoir pressure. If similar heads are obtained from top and bottom gauge readings, gauge readings are probably reliable since both gauges are not likely to be in error by the same amount. Also, sometimes a check on the accuracy of the gauge can be made if the mud weight is known; the hydrostatic mud pressure, calculated from mud weight and gauge depth, can be compared with the observed mud pressure.

The amount of liquid fill-up during the DST gives further evidence of the quality of the reservoir pressure data obtained in the test. Small fill-up is an indication of low permeability; therefore, shut-in pressures after the flow period may be unreliable. In this case the ICIP may be the most reliable value. Large fill-up is an indication of high permeability. Even when the ICIP and FCIP differ somewhat, a good estimate of the reservoir pressure often can be made by plotting log $[(t + \theta)/\theta]$ vs. shut-in pressure and extrapolating to log $[(t + \theta)/\theta] = 0$ (Dolan et al., 1957; van Poollen, 1961).

In the present study, after the best estimate of reservoir pressure had been made from the DST data, the pressure, in pounds per square inch, was converted to equivalent feet of fresh-water head by multiplying by the factor 2.31. That is, equivalent feet of fresh water = 2.31 x reservoir pressure (psig).



$H^{1.00}$ = elevation + [(equivalent feet of fresh-water head) — (gauge depth)]

Drill-stem test pressures are generally reported as gauge pressures, psig. Values of $H^{1.00}$ calculated in the manner described above, using psig, can be compared directly with values of $H^{1.00}$ derived from water-level observations. In a few cases absolute reservoir pressures were reported (psia). In each of these cases one atmosphere, 14.7 psi, was subtracted from the reported psia reading to give psig; this psig value was then used to calculate a value of $H^{1.00}$ that would be consistent with the values of $H^{1.00}$ that were derived from the results of water-level and DST observations.

In a few instances estimates of $H^{1.00}$ were made from the fill-up data given for DST tests. These estimates generally were of questionable validity because of uncertainties about whether or not equilibrium was reached as well as uncertainty about the density of the liquids recovered in the DST. They did serve to give a lower limit of $H^{1.00}$ because we had some assurance that $H^{1.00}$ was at least as high as the value calculated from the fill-up data.

TABLE 1 - HYDRODYNAMIC DATA —

Reservoir or project	Company	Well	Location: County	Location: Sec., T.,R.	Stratigraphic unit	Well-head elevation: Ft	Well-head elevation: Reference point*	Observation point	Depth to observation point (ft)	Z, observation point	Produced water: ρ	Produced water: TDS (mg/l)
ILLINOIS												
Ancona	No. Ill. Gas	Fordyce No. 1	Livingston	33,30N,3E	Mt. S.	640	NIG Std.	Top perfs.	2178	-1538	1.011	17,900
	No. Ill. Gas	Krischel No. 2	Livingston	24,30N,2E	Mt. S.	663	NIG Std.	Top perfs.	2508	-1845	1.011	18,448
	No. Ill. Gas	Scheuer No. 1	La Salle	14,30N,2E	Mt. S.	667	NIG Std.	Top perfs.	2203	-1536	1.006	13,174
	No. Ill. Gas	Barr No. 1	La Salle	22,30N,2E	Mt. S.	671	NIG Std.	Top perfs.	2370	-1699	1.006	12,258
Brookville	Nat'l. Gas Pipeline		Ogle	41N,7E	Mt. S. Eau Cl.			Top perfs.			1.00 1.00	
Crescent City	No. Ill. Gas		Iroquois	26-27N,13W	Mt. S. "A"	654	NIG Std.	Top perfs.	3400	-2746	1.061 est.	86,600
					Mt. S. "B"	656	NIG Std.	Top perfs.	3580	-2924	1.068 est.	96,202
		Taden No. 209	Iroquois	11,26N,13W	Mt. S. "A"	648	G.L.	Press. bomb	3971	-3323	1.061	86,600
		Taden No. 201	Iroquois	11,26N,13W	Mt. S. "B"			Press. bomb		-2954		
Dale	Texaco	Cuppy No. 1	Hamilton	6,65,7E	Eau Cl.	393	K.B.	Top ga.	11,793	-11,400	1.128	212,179
								Bottom ga.	11,812	-11,419		
Erp	Nelson-Erp & Stroh	Erp No. 1	Ford	19,24N,7E	Mt. S.	828	G.L.	Top Mt. S.	4220	-3392	1.039 est.	57,600
Hennepin	Jones & Laughlin	Waste-disposal well No. 1	Putnam	3,32N,2W	Mt. S.	527	K.B.	Top Mt. S.	3109	-2582	1.041 est.	61,600
Herscher	Nat'l. Gas Pipeline	Karcher No. 6	Kankakee	32,30N,10E	Mt. S.	678	K.B.	Top Mt. S.	2439	-1761	1.013	18,940
Herscher NW	Nat'l. Gas Pipeline	P. Cook No. 1	Kankakee	3,30N,9E	Mt. S.	622	K.B.	Top Mt. S.	2204	-1582	1.004	9362
Hudson	No. Ill. Gas	Schlosser No. 1	McLean	32,25N,3E	Mt. S.	776	NIG Std.	Top perfs.	3956	-3180	1.053	74,450
Lake Bloomington	No. Ill. Gas	J. Anderson No. 1	McLean	31,26N,3E	Mt. S.	727	NIG Std.	Top perfs.	3608	-2881	1.045	59,650
	No. Ill. Gas	Furrow No. 4	McLean	31,26N,3E	Eau Cl.	748	NIG Std.	Top perfs.	3276	-2528	1.022	
Lamb	Peoples Gas	Lamb No. 1	De Witt	1,20N,4E	Mt. S.	732	Orbit-stem valve	Top perfs.	4570	-3834	1.074	107,115
Lexington	No. Ill. Gas		McLean		Mt. S.				3710	-2968	1.045	65,220
	No. Ill. Gas	Pyne No. 1	McLean	14,25N,3E	Mt. S.	742	NIG Std.	Top perfs.	3752-3772	-3010	1.052	65,220
	No. Ill. Gas	Smith No. 1	McLean	20,25N,4E	Mt. S.	746	NIG Std.	Top perfs.	3857-3943	-3111	1.051	64,480
	No. Ill. Gas	Moore No. 1	McLean	22,25N,3E	Mt. S.	781	NIG Std.	Top perfs.	3908-3994	-3127	1.050	68,460
	No. Ill. Gas	Cook No. 1	McLean	14,25N,3E	Mt. S.	728	NIG Std.	Top perfs.	3726-3762	-2998	1.051	65,460
Louden	Humble	Weaber-Horn No. 1	Fayette	28,8N,3E	Mt. S.	538	K.B.	Top ga.	7978	-7440		
Mahomet	Peoples Gas	A. G. Hunt No. 5	Champaign	17,21N,7E	Mt. S.	739	G.L.	Top perfs.	3942	-3203	1.059	90,000
	Peoples Gas	Fee No. 1	Champaign	9,21N,7E	Mt. S.	742	G.L.	Top perfs.	3931-4010	-3189	1.061	82,600
Momence		Momence	Kankakee	24,31N,13E	Mt. S.	628	G.L.	T.D.	2800	-2172	1.025 est.	38,000
Pecatonica	Cent. Ill. Elec. & Gas	Wright No. 202	Winnebago	2,26N,10E	"Lightsville" Eau Cl.	861	G.L.	Top perfs.	820	+ 41	1.00	
Pontiac	No. Ill. Gas	Fienhold No. 1	Livingston	33,28N,6E	Mt. S.	732	NIG Std.	Top perfs.	3008	-2276	1.034	50,800
	No. Ill. Gas	Fienhold No. 4	Livingston	33,28N,6E	Eau Cl.	713	K.B.	Top perfs.	2659	-1946	1.018	27,300
St. Jacob	Miss. R. Fuel	E. F. Kircheis No. S-1	Madison	27,3N,6W	Mt. S.	504	K.B.	Top ga.	4940	-4436	1.07 est.	98,500
								Bottom ga.	5013	-4509		
Salem	Texaco	R. S. Johnson No. 1	Marion	6,1N,2E	Mt. S.	541	K.B.	Top ga.	8892	-8351	1.165	262,962
								Bottom ga.	8929	-8388		
Shanghai	Ill. Power	Moberg No. 1	Warren	3,12N,1W	Eau Cl.	737	G.L.	Top perfs.	2466	-1729	1.005	4100
South	R. E. Davis	E. A. South No. 1	Henry	30,16N,1E	Mt. S.	793	G.L.	Top ga.	2636	-1843	1.004	5900

*NIG Std. — Northern Illinois Gas Standard (=5.5 feet above casing flange); G.L. — ground level; K.B. — kelly bushing.
**The value underlined is considered to be the most reliable value.

ILLINOIS BASIN AND SURROUNDING AREA: MT. SIMON

Water-level measurements			Reservoir pressure, from pressure bomb (psig)	Drill-stem tests								$H^{1.00}$**				Remarks
Observed water level, S.L. (ft)	Length of observed water column ($L_{obs.}$)	Length of equiv. fresh-water column ($\rho \times L_{obs.}$)		ICIP (psig)		FCIP (psig)		Pressure at $\theta \rightarrow \infty$ (psig)		Equiv. ft fresh water (2.31 x psig)		From water-level observation	From reservoir pressure	From drill-stem test		
				Top ga.	Bottom ga.	Top ga.	Bottom ga.	Top ga.	Bottom ga.	Ft	Derived from			Top ga.	Bottom ga.	
616	2154	2178	945							2183	Reserv. press.	640	645			TDS at Ancona varies from 17,900 to 25,800 mg/l
620	2465	2492										647				
622		2171										635				
624		2337										638				
648												648				
652												652				
516	3262	3461										715				
505												738				
517	3840	4074	1768							4084	Reserv. press.	751	761			
505	3459		1591										721			
				5095				5840		13,490	Extrap. press.			2090		$H^{1.00}$ is at least 836
										11,769	ICIP			369		
					5090				5840	13,490	Extrap. press.				2071	Extrapolation not considered reliable
			5297							12,236	Mud press.			836		Observed pressure is mud pressure, top gauge
																Depth of water sample not known
623	2384	2415	1045							2414	Reserv. press.	654	653			
638	2220	2229	976							2255	Reserv. press.	647	673			$H^{1.00}$ influenced by previous gas injection at Herscher
531	3707	3903										723				$H^{1.00}$ ranges from 721 to 736
543	3424	3578	1565 (at -2900 S.L.)							3615	Reserv. press.	697	715			$H^{1.00}$ ranges from 695 to 711
555	3083	3151										623				
458	4296	4614										776				
530	3540	3724										714				Ave. $H^{1.00}$ = 718
536	3647	3833										722				
537	3664	3847										720				
536	3534	3714										716				
				3630		3605		3666		8468	Extrap. press.			1028		
535	3738	3959	1700 at 3942'							3927	Reserv. press.	756	724			
																Open interval in well not known
686	645	645										686				
576	2852	2949	1335									673				
500	2446	2490										544				
			2153	2151		2153				4973	FCIP			537		Ave. $H^{1.00}$ = 567
					2210		2210								596	
				3707		3642		4050		9356	Extrap. press.			1005		$H^{1.00}$ calculated from extrapolated pressure
					3725		3659		4080	9425	Extrap. press.				1037	Ave. $H^{1.00}$ = 1021
619	2348	2360										631				
505 (DST recovery)	2348	2357				1070				2472	FCIP	514 (DST recovery)		629		

(continued on the following pages)

Reservoir or project	Company	Well	Location		Stratigraphic unit	Well-head elevation		Observation point	Depth to observation point (ft)	Z, observation point	Produced water	
			County	Sec., T.,R.		Ft	Reference point*				ρ	TDS (mg/l)
I L L I N O I S continued												
Swensen	Otto	Swensen No. 1	La Salle	1,36N,5E	Mt. S.	659	G.L.	Top perfs.	3464-3470	-2805	1.047 est.	67,000
Troy Grove	No. Ill. Gas	P. Matheius No. 1	La Salle	32,35N,1E	Mt. S.	683	NIG Std.		1421	-738	1.00	2330
					Eau Cl. "A" Eau Cl. "B"							2440
Tuscola	Panhandle Eastern	Bristow No. 1-4	Douglas	4,16N,8E	Mt. S.	679	G.L.	Top ga.	3995	-3316	1.081 est.	113,144
									4038	-3359	1.09	
								Bottom ga.	4040	-3361		
	Ohio Oil	Shaw No. 1	Douglas	36,16N,8E	Mt. S.	666	G.L.		4046-4060	-3380	1.073 est.	103,000
									4063-4085	-3397	1.090* est.	128,000
Waterloo	Miss. R. Fuel	Theobald No. A-15	Monroe	35,1S,10W	Eau Cl.	666	G.L.		2750	-2084	1.013 est.	20,000
Waverly	Panhandle Eastern	Whitlock No. 7-15	Morgan	15,13N,8W	Mt. S.	640			4100	-3460	1.035	51,461
West Chicago	Am. Potash & Chemical	Waste-disposal well No. 1	Du Page	9,39N,9E	Mt. S.	734	G.L.		2200	-1466	1.00	
									2500	-1766	1.003	
									3000	-2266	1.02	
									3900	-3166	1.07	
I N D I A N A												
Gary Area	Inland Steel	Waste-disposal well	Lake	14,37N,9W	Mt. S.	608	K.B.	DST interval	3870-3895	-3262	1.090	123,000
					Mt. S.			DST interval	2582-2600	-1974	1.016	20,100
	U. S. Steel	Waste-disposal well	Lake	29,37N,8W	Mt. S.				2469-2491	-1869	1.010	13,200
					Mt. S.	600	K.B.	DST interval	3316-3333	-2716	1.071	97,800
					Mt. S.			DST interval	3793-3813	-3193	1.092	124,000
					Mt. S.				2420	-1820		
					Eau Cl.				2109-2142	-1509		
	Midwest Steel	Waste-disposal well	Porter	25,37N,7W	Eau Cl. & Mt. S.	615	K.B.	DST interval	2160-4259	-1545 to -3644	1.04 est.	59,590
					Mt. S.			Top ga.	3416	-2801		
					Eau Cl.			Top ga.	1802	-1187		
					Eau Cl.			Top ga.	1625	-1010		
	Bethlehem Steel	Waste-disposal well	Porter	28,37N,6W	Eau Cl. & Mt. S.	625	K.B.	DST interval	1865-2918	-655		1280
					Mt. S.			DST interval	2210-4292	-1585 to -3667	1.048 est.	71,370
Lake of the Woods, East	No. Ind. Pub. Serv.	No. LWE-88	Marshall	21,34N,3E	Mt. S.	789	G.L.	Top ga.	2982	-2193	1.100	~34,000 (ppm Cl)
								Bottom ga.	2986	-2197		
					Eau Cl.	789	G.L.	Top ga.	2704	-1915	1.00	~ 5,000 (ppm Cl)
								Bottom ga.	2708	-1919		
Lakeside	No. Ind. Pub. Serv.	No. L-1-1	Pulaski	26,29N,3W	Eau Cl.	686	G.L.	Top ga.	2293	-1607	1.05	
								Bottom ga.	2308	-1622		
					Eau Cl.			Top ga.	2387	-1701	1.05	
								Bottom ga.	2474	-1788		
					Mt. S.			Top ga.	2639	-1953	1.05	
								Bottom ga.	2726	-2040		
Newport	Food Mach. & Chemical	Waste-disposal well	Vermillion	9,16N,9W	Mt. S.	650	K.B.	DST interval	5450-6160	-4800 to -5510	1.148	234,700
Royal Center	No. Ind. Pub. Serv.	No.S-106	Fulton	14,28N,1W	Mt. S. "A"			Top perfs.	2770	-2021	1.045 est.	68,800 est. from Cl
					Mt. S. "B"				2862	-2113	1.074 est.	104,400 est. from Cl
					Mt. S. "basement"				3991	-3242	1.090 est.	124,200 est. from Cl
	No. Ind. Pub. Serv.	No.S-111-2	Fulton	20,29N,1E	Mt. S.	740	G.L.	Top ga.	2880	-2140	1.075	
								Bottom ga.	2913	-2173		
	No. Ind. Pub. Serv.	No.S-111-2	Fulton	20,29N,1E	Mt. S.	740	G.L.	Top ga.	2784	-2044	1.065	
								Center ga.	2823	-2083		
	No. Ind. Pub. Serv.	No.S-94-2	Fulton	30,29N,1E	Eau Cl.	748	G.L.	Top ga.	2581	-1833	1.055	
								Bottom ga.	2605	-1857		
	No. Ind. Pub. Serv.	No.S-95	Fulton	30,29N,1E	Galesville-Mt. S.	750	G.L.	Top perfs.	2164	-1414	1.067	
	No. Ind. Pub. Serv.	No.S-84	Cass	14,28N,1W	Mt. S. "B"	732	G.L.	Top perfs.	2906	-2174	1.062	
	No. Ind. Pub. Serv.	No.S-76	Cass	17,28N,1W	Mt. S. "B"	749	G.L.	Top perfs.	2958	-2209	1.062	
	No. Ind. Pub. Serv.	No.S-55	Cass	17,28N,1W	Mt. S. "A"	745	G.L.	Top perfs.	2958	-2213	1.067	

*NIG Std. – Northern Illinois Gas Standard (= 5.5 feet above casing flange); G.L. – ground level; K.B. – kelly bushing.
**The value underlined is considered to be the most reliable value.

continued

Water-level measurements: Observed water level, S.L. (ft)	Water-level measurements: Length of observed water column ($L_{obs.}$)	Water-level measurements: Length of equiv. fresh-water column ($\rho \times L_{obs.}$)	Reservoir pressure, from pressure bomb (psig)	Drill-stem tests: ICIP (psig) Top ga.	Drill-stem tests: ICIP (psig) Bottom ga.	Drill-stem tests: FCIP (psig) Top ga.	Drill-stem tests: FCIP (psig) Bottom ga.	Drill-stem tests: Pressure at $\theta \rightarrow \infty$ (psig) Top ga.	Drill-stem tests: Pressure at $\theta \rightarrow \infty$ (psig) Bottom ga.	Drill-stem tests: Equiv. ft fresh water (2.31 x psig) Ft	Drill-stem tests: Equiv. ft fresh water (2.31 x psig) Derived from	$H^{1.00**}$: From water-level observation	$H^{1.00**}$: From reservoir pressure	$H^{1.00**}$: From drill-stem test Top ga.	$H^{1.00**}$: From drill-stem test Bottom ga.	Remarks
645	1383	1383	600 at -760'							1386	Reserv. press.	645	626			
617												617				
629												629				
				1755		1741		1757		4059	Extrap. press.			743 Extrap. press.		
246	3792	4133										773				
					1778		1764		1781	4114	Extrap. press.				753 Extrap. press.	
																Data from Graf et al., 1966, table 3, p. 49
								1420		3280	Extrap. press.			580		Pressure measured at -2700 feet
								1020		2356	Extrap. press.			536		
								888		2051	Extrap. press.			542		
																Interval = 2099 feet
				1412		1415				3269	FCIP			468		
				687		687				1587	FCIP			400		
				614		614				1418	FCIP			418		
																Poor sample
577	2770 (DST recovery)	3047		1216		1217				2811	FCIP	854		618		
					1220		1223			2825	FCIP				628	
-592	1323 (DST recovery)	1323		1096		1075				2483	FCIP	-592 (DST recovery)		568		
					1102		1082			2499	FCIP				580	
-1197	410 (DST recovery)	431		868		841		940		2171	Extrap. press.	-1156 (DST recovery)		564		
					905		879		980	2264	Extrap. press.				642	
319	2020 (DST recovery)	2121		964		971		982		2268	Extrap. press.	420 (DST recovery)		567		
					1003		1011		1020	2356	Extrap. press.				568	
367	2320 (DST recovery)	2436		1091		1099		1100		2541	Extrap. press.	483 (DST recovery)		588		
					1130		1138		1140	2633	Extrap. press.				593	
290	5090	5843										1043				Note large open interval
																Contaminated sample ?
355	2495 (DST recovery)	2682		1174		1179				2723	FCIP	542 (DST recovery)		583		
					1194		1195			2760	FCIP				587	
-544	1500 (DST recovery)	1597		1111		1118				2583	FCIP	-447 (DST recovery)		539		
					1135		1142			2638	FCIP				555	
-813	1020 (DST recovery)	1076		1048		1044				2412	FCIP	-757 (DST recovery)		579		
					1061		1056			2439	FCIP				582	
435	1849	1973										559				
450	2624	2787										613				
620	2829	3004										795				
582	2795	2982										769				Remark for S-85 and S-94 also applies here

(continued on the following pages)

TABLE I - HYDRODYNAMIC DATA -

Reservoir or project	Company	Well	Location: County	Location: Sec., T.,R.	Stratigraphic unit	Well-head elevation: Ft	Well-head elevation: Reference point*	Observation point	Depth to observation point (ft)	Z, observation point	Produced water: ρ	Produced water: TDS (mg/l)
Royal Center continued												
	No. Ind. Pub. Serv.	No.S-85	Cass	12,28N,1W	Mt. S. "B"	737	G.L.	Top perfs.	2904	-2167	1.064	
	No. Ind. Pub. Serv.	No.S-94	Fulton	30,29N,1E	Mt. S. "A"	748	G.L.	Top perfs.	2785	-2037	1.073	
	No. Ind. Pub. Serv.	No.S-79	Fulton	30,29N,1E	Mt. S. "B"	749	G.L.	Top perfs.	2898	-2149	1.068	
	No. Ind. Pub. Serv.	No.S-99	Fulton	30,29N,1E	Eau Cl. No. 2-Glsvl.	749	G.L.	Top perfs.	2510	-1761		
M I C H I G A N												
Boyd	Consumers Power	Brine disposal No. 1	St. Clair	31,4N,15E	Mt. S.	608	G.L.	DST interval	4496-4627	-3888 to -4019	1.191	318,500
Holland	Holland Suco Color Co.	Disposal well No. 1	Ottawa	30,5N,15W	Dundee-Detroit River	623	K.B.	DST interval	1680-1893		1.165	235,950
					Detroit River				1928-1940			153,450
					Trempealeau-Franconia-Eau Cl.				4615-4805		1.18	160,000 (Chlorides)
					Eau Cl.-Mt. S.				4866-5894		1.16	155,000 (Chlorides)
			Livingston		Dresbach (Cambrian)						1.227	30,000 (ppm Ca)
I O W A												
Cairo	Nat'l. Gas Pipeline		Louisa		Mt. S.			Perfs.		~ -1650	1.007 est.	11,000
Columbia City	Nat'l. Gas Pipeline		Louisa		Mt. S.			Perfs.		~ -1650	1.007 est.	10,000
Redfield	No. Nat'l. Gas	Hummel No. 1	Dallas	18,79N,28W	Mt. S.	1050 est.	G.L.	Top ga.	2731	-1681	1.00	1782
Vincent	No. Nat'l. Gas	Peterson No. 1	Webster	10,90N,27W	Mt. S.	1144	K.B.	Top ga.	2160	-1016	1.009 est.	13,188
Wapello	Nat'l. Gas Pipeline		Louisa		Mt. S.			Perfs.		~ -1650	1.007 est.	

*NIG Std. — Northern Illinois Gas Standard (=5.5 feet above casing flange); G.L. — ground level; K.B. — kelly bushing.
**The value underlined is considered to be the most reliable value.

continued

Water-level measurements			Reservoir pressure, from pressure bomb (psig)	Drill-stem tests								$H^{1.00**}$				Remarks
Observed water level, S.L. (ft)	Length of observed water column ($L_{obs.}$)	Length of equiv. fresh-water column ($\rho \times L_{obs.}$)		ICIP (psig)		FCIP (psig)		Pressure at $\theta \to \infty$ (psig)		Equiv. ft fresh water (2.31 x psig)		From water-level observation	From reservoir pressure	From drill-stem test		
				Top ga.	Bottom ga.	Top ga.	Bottom ga.	Top ga.	Bottom ga.	Ft	Derived from			Top ga.	Bottom ga.	
440	2607	2773										606				Other water-level & pressure data indicate flow, which is probably toward the north or northeast
440	2589	2765										616				
392	2153															
	3240 (DST recovery)					2088				4823	FCIP			935		Gauge assumed to be at top of DST interval
																Note high calcium content of water
661	2311	2327										677				
663	2313	2329										679				
864	2545	2545				1110				2564	FCIP	864		883		
				840		839				1940	ICIP			924		
660	2310	2326										676				

TABLE 2 - HYDRODYNAMIC DATA —

Reservoir or project	Company	Well	Location: County	Location: Sec., T.,R.	Stratigraphic unit	Well-head elevation: Ft	Well-head elevation: Reference point*	Observation point	Depth to observation point (ft)	Z, observation point	Produced water: ρ	Produced water: TDS (mg/l)
I L L I N O I S												
Ancona	No. Ill. Gas	Fordyce No. 3	Livingston	33,30N,3E	Galesville	640	NIG Std.	Top perfs.	1724	-1084	1.00	3785
	No. Ill. Gas		La Salle	30N,2E	Galesville				1708	-1045		6658
Brookville	Nat'l. Gas Pipeline		Ogle	41N,7E	Galesville			Top perfs.			1.00	
					Franconia			Top perfs.			1.00	
Clay City	Union of California	Cisne Comm. No. 1	Wayne	3,1S,7E	Shakopee	504	K.B.	Top ga.	7734	-7230	1.076	106,000
								Bottom ga.	7772	-7268		
Crescent City	No. Ill. Gas		Iroquois	26,27N,13W	Galesville	650	NIG Std.	Top perfs.	2650	-2000	1.039	55,700
Dale	Texaco	Cuppy No. 1	Hamilton	6,6S,7E	Potosi	393	K.B.	Top ga.	9649	-9256	1.135	
								Bottom ga.	9663	-9270		
Dupo	Victor Nettle	Nettle No. 1	St. Clair	33,1N,10W	Knox	466	G.L.		1741-1760	-1275		
					Franconia				2456-2548	-1990		
Hennepin	Am. Ind. Waste Disposal Syst., Inc.	Waste-disposal well No. 1	Putnam	3,32N,2W	Franconia-Ironton-Galesville	519	R.B.	Top ga.	2290	-1771		15,000
								Bottom ga.	2698	-2179		
Herscher	Nat'l. Gas Pipeline	Karcher No. 8	Kankakee	28,30N,10E	Galesville	676	G.L.	Top Glsvl.	1757	-1081	1.006	2528
Herscher NW	Nat'l. Gas Pipeline	P. Cook No. G-1	Kankakee	3,30N,9E	Galesville	611	G.L.	Top Glsvl.	2269	-1658	1.006 (?)	1435
Hudson	No. Ill. Gas	Grimes No. 3	McLean	1,24N,2E	Galesville	795	NIG Std.	Top perfs.	3287	-2492	1.005	7480
Lake Bloomington	No. Ill. Gas	Furrow No. 4	McLean	31,26N,3E	Galesville	713	NIG Std.	Top perfs.	2996	-2283	1.001	1955
Lexington	No. Ill. Gas	Cook No. 2	McLean	14,25N,3E	Galesville	743	NIG Std.	Top perfs.	3157-3167	-2414	1.00	1410
Mahomet	Peoples Gas	Fee No. 3	Champaign	9,21N,7E	Galesville	758	K.B.	Top perfs.	3272-3292	-2514	1.026	
	Peoples Gas	G. Webster No. 1	Champaign	17,21N,7E	Galesville	758	K.B.	Top perfs.	3277-3297	-2519	1.026	37,000
Pecatonica	Central Ill. Electric & Gas	Wright No. 401	Winnebago	2,26N,10E	Galesville	862	G.L.	Top Glsvl.	680	+182	1.00	
Pickel	Humble	J.E. Pickel No. 1	Union	21,13S,2W	Knox	424	K.B.	Top ga.	5695	-5271	1.073 est.	101,000
								Bottom ga.	5792	-5368		
Pontiac	No. Ill. Gas	Fienhold No. 3	Livingston	33,28N,6E	Galesville	711	K.B.	Top perfs.	2457	-1746	1.00	1300
Shanghai	Ill. Power Co.	Anderson No. 1	Warren	7,12N,1W	Galesville	701	G.L.	Top Glsvl.	2118	-1417	1.00	1235
		Moberg No. 2	Warren	3,12N,1W	Franconia	700	G.L.	Top Franconia	1980	-1280	1.00	480
South	R. E. Davis	E.A. South No. 1	Henry	30,16N,1E	Ironton-Galesville	793	G.L.	Top ga.	2290	-1497	1.002	4400
Troy Grove	No. Ill. Gas	Amfahr No. 3	La Salle	29,35N,1E	Galesville	691	NIG Std.	Top Glsvl.			1.00	
Troy Grove	No. Ill. Gas	Weldon No. 9	La Salle	5,34N,1E	Galesville	678	NIG Std.		910	-227		720
Tuscola	Cabot Corp.	Cabot No. 1	Douglas	31,16N,8E	Knox	689	G.L.	Knox	4861	-4172		
	U.S. Industrial Chem.	USI disposal well No. 1	Douglas	31,16N,8E	Knox	708	K.B.	Top Knox	5150	-4442		
	Amgo & Botts	Buck No. 2	Douglas	31,16N,8E	Trempealeau	696	K.B.	Top ga.	5126	-4430	1.01 est.	16,900
Waverly	Panhandle Eastern	Criswell No. 1-16	Morgan	16,13N,8W	Galesville	658	G.L.	Pressure ga.	3622	-2964	1.00	2147
I N D I A N A												
Gary	U.S. Steel	Waste-disposal	Lake	29,37N,8W	Galesville	600	K.B.	Gauge	1800-1830	-1200	1.004	4470
Lake of the Woods, East	No. Ind. Pub. Serv.	H. Ames No. 1	Marshall	21,34N,3E	Galesville (some Eau Cl.)	789	G.L.	Top ga.	2385	-1596	1.028 est.	
								Bottom ga.	2389	-1600		
Royal Center	No. Ind. Pub. Serv.	No.5-95	Fulton	30,29N,1E	Galesville				2200	-1451	1.045 est.	64,800
	No. Ind. Pub. Serv.	No.4-5-99	Fulton	30,29N,1E	Galesville	740	G.L.	Top ga.	2155	-1415	1.035	
								Center ga.	2169	-1429	1.035	
	No. Ind. Pub. Serv.	No.S-111-2	Fulton	20,29N,1E	Galesville	740	G.L.	Top ga.	2076	-1336	1.025	
								Bottom ga.	2120	-1380		
	No. Ind. Pub. Serv.	No.1-S-55	Cass	32,29N,1E	Ironton-Galesville	745	G.L.	Top ga.	2082	-1337	1.025	
								Bottom ga.	2114	-1369		
	No. Ind. Pub. Serv.	No.1-S-55	Cass	32,29N,1E	Franconia	745	G.L.	Top ga.	2011	-1266	1.025	
								Bottom ga.	2043	-1298		
M I C H I G A N												
Tipton			Tipton	21,21N,3E	Knox				1512-1520		1.004	6663
Monroe			Monroe	29,8N,1E	Knox				2489			16,343 (ppm)
Holland	Holland Suco Color Co.	Waste-disposal well No. 2	Ottawa	30,5N,15W	Franconia	620	R.T.	Gauge	4666	-4046	1.08	
I O W A												
Cairo	Nat'l. Gas Pipeline		Louisa		Galesville			Perfs.			1.00	

*NIG Std. — Northern Illinois Gas Standard (= 5.5 feet above casing flange); K.B. — kelly bushing; G.L. — ground level; R.T. — rotary table.
**The value underlined is considered to be the most reliable value.
***$H^{1.00}$ calculated from DST recovery.

ILLINOIS BASIN AND SURROUNDING AREA: IRONTON-GALESVILLE THROUGH KNOX

Water-level measurements: Observed water level, S.L. (ft)	Water-level measurements: Length of observed water column ($L_{obs.}$)	Water-level measurements: Length of equiv. fresh-water column ($\rho \times L_{obs.}$)	Reservoir pressure, from pressure bomb (psig)	Drill-stem tests: ICIP (psig) Top ga.	Drill-stem tests: ICIP (psig) Bottom ga.	Drill-stem tests: FCIP (psig) Top ga.	Drill-stem tests: FCIP (psig) Bottom ga.	Drill-stem tests: Pressure at $\theta \to \infty$ (psig) Top ga.	Drill-stem tests: Pressure at $\theta \to \infty$ (psig) Bottom ga.	Drill-stem tests: Equiv. ft fresh water (2.31 x psig) Ft	Drill-stem tests: Equiv. ft fresh water Derived from	$H^{1.00}$** From water-level observation	$H^{1.00}$** From reservoir pressure	$H^{1.00}$** From drill-stem test Top ga.	$H^{1.00}$** From drill-stem test Bottom ga.	Remarks
496	1580	1580										496				
682												682				
723												723				
				3337		3254		3506		8099	Extrap. press.			869		Ave. $H^{1.00}$ = 913
					3404		3325		3560	8224	Extrap. press.				956	
411	2411	2505										505				
				4312		4219		4490		9961	ICIP			704		$H^{1.00}$ from ICIP
										10372	Extrap. press.				1116	$H^{1.00}$ from Extrap. press
	1465 (DST recovery)								720 BHP	1663					388	BHP = Bottom-hole press.
	240 (DST recovery)								1042 BHP	2407					417	
						1001				2312	FCIP			541		
							1170			2716	FCIP				537	Ave. $H^{1.00}$ = 539
471	1552	1561	700 at -1100'							1617	Reserv. press.	480	517			
456	2114	2127										469				
511	3003	3018										526				
510	2793	2796										513				
512	2926	2926										512				
464	2872	2947	1285± at -2408'							2968	Reserv. press.	433	560			
458	2977	3055										536				
716	534	534										716				
				2581		2582				5962	FCIP			691		
					2589		2591			5983	FCIP				615	
515	2261	515	843									515				Depth of pressure reading is uncertain
513	1930	513										513				
514	1794	514										514				
443 (DST recovery)	1940	1944				870				2010	FCIP	447 (DST recovery)		513		
605±												605				Level fluctuates because of industrial use of water
595±	822											595				Level fluctuates because of industrial use of water
539	4711		2035							4701	Reserv. press.	539		529		Density of water in well at time of W.L. observation is not known
528	4970											528				Hole contained fresh water at time W.L. was measured
340	4770 (salty water)	4967		2211		2150				4813	ICIP	380		529		Water level calculated from recovery in DST is questionable
526	3490	526	1527							3527	Reserv. press.	526	563			
								~695		1605			405			
434	2030 (DST recovery)	2087		918		920				2125	FCIP	491 (DST recovery)		529		$\rho_{est.}$=1.028 from other sources. Ave. = 534
					924		926			2139	FCIP				539	
405 (DST recovery)	1820	1884		823		820				1901	ICIP	469***		486		
					830		828			1917	ICIP				488	
344 (DST recovery)	1680	1722		792		794				1834	FCIP	386***		498		
					812		813			1878	FCIP				498	
436 (DST recovery)	1730	1773		794		797				1841	FCIP	436***		504		
					810		812			1876	FCIP				507	
163 (DST recovery)	1500	1537		766		766				1769	FCIP	271***		503		
					773		774			1788	FCIP				490	
524	4000' water + 570' drilling fluid	4890		2158		2158				4985	FCIP	844 (DST recovery)		939		
544												544				

TABLE 3 - HYDRODYNAMIC DATA —

Reservoir or project	Company	Well	Location		Stratigraphic unit	Well-head elevation		Observation point	Depth to observation point (ft)	Z, observation point	Produced water	
			County	Sec., T.,R.		Ft	Reference point*				ρ	TDS (mg/l)
I L L I N O I S												
Ancona	No. Ill. Gas	Clark No. 1	Livingston	33,30N,3E	St. P.	636	NIG Std.	Top perfs.	348	+ 288	1.00	1205
Brohammer	Phillips	Brohammer No. 1	Montgomery	20,7N,2W	St. P.	617	D.F.	Top perfs.	3752	-3135	1.009 est.	13,900
Crescent City	No. Ill. Gas	J. Taden No. 2	Iroquois	11,26N,13W	St. P.	655	K.B.	Top perfs.	1224	-569	~ 1.00	2239
Dale	Texaco	Cuppy No. 1	Hamilton	6,6S,7E	St. P.	393	K.B.	Top ga.	7608	-7215	1.125	204,500 (DST recovery)
								Bottom ga.	7628	-7235		
Ford	Superior	H.C. Ford et al. No. C-17	White	27,4S,14W	St. P.	386	K.B.	Top ga.	7335	-6949	1.14 est.	199,000
Lamb-Walden	Peoples Gas	Lamb No. 1	De Witt	1,20N,4E	St. P.	732	Orbit-stem valve	Top perfs.	2275	-1543	1.005	3308
		Walden No. 1	De Witt	29,21N,4E	St. P.	749	Orbit-stem valve	Top perfs.	2407	-1658	1.005	3242
Louden	Carter	J. Brauer No. 6-D	Fayette	21,8N,3E	St. P. & Knox	528	D.F.	Top perfs.	4455	-3927	1.003	3558
Mahomet	Peoples Gas	A.G. Hunt No. 5	Champaign	16,21N,7E	St. P.	755	K.B.	Top St. P.	1540	-785	1.003 ave.	1715-3134
Pecatonica	Cent. Ill. Elec. & Gas	Gustafson No. 601 WB	Winnebago	34,27N,10E	St. P.	842	G.L.	Top St. P.	169	+673	1.00	
Plymouth	Marathon	Lyon Hrs. No. CT-1	McDonough	19,4N,4W	St. P.	616	K.B.	Top ga.	928	-312		
								Bottom ga.	944	-328		
Pontiac	No. Ill. Gas	Fienhold No. 200	Livingston	28,28N,6E	St. P.						1.00±	1394
Rodda	Magnolia	M.T. Rodda No. 1	Coles	4,11N,9E	St. P.	611	K.B.	Top ga.	5253	-4642		
		M.T. Rodda No. 1			Glenwood	611	K.B.	Top ga.	5224	-4613		
Ryan	L. Harris	Cora Ryan No. 4	De Witt	21,21N,3E	St. P.	810	K.B.	Top ga.	2174	-1364	1.00	1486
								Bottom ga.	2186	-1376		
St. Jacob	Miss. R. Fuel	E.F. Kircheis No.S-1	Madison	27,3N,6W	St. P.	504	K.B.	Top ga.	2837	-2333		
								Bottom ga.	2924	-2420		
Salem	Texaco	R.S. Johnson No. 1	Marion	6,1N,2E	St. P.	541	K.B.	Top ga.	5220	-4679	1.075	112,000
								Bottom ga.	5262	-4721		
Shanghai	Ill. Power Co.	Moberg No. 5	Warren	3,12N,1W	Glenwood & St. P.	685	G.L.	Top Glenwood	944	-259	1.00	
South	R.E. Davis	E.A. South No. 1	Henry	30,16N,1E	St. P.	793	G.L.	Top ga.	1290	-497	1.006	11,280
Tuscola	Ill. Power Co.	Debolt No. 1	Douglas	4,16N,8E	St. P.	671	G.L.	Top perfs.	1479	-808	1.014	20,928
		Bristow No. 1	Douglas	4,16N,8E	St. P.	683	G.L.	Top perfs.	1506	-823	1.004	7114
		Koss No. 1	Champaign	21,17N,8E	St. P.	694	G.L.	Csg. seat	1640	-946	1.012	19,606
		Waltrip No. 1	Douglas	26,16N,8E	St. P.	664	G.L.	Csg. seat	1519	-855	1.014	22,706
		Municipal water well	Douglas	34,16N,8E	St. P. & Gal.-Ptv.	655					1.00	
M I C H I G A N												
Barry	Sun Oil		Barry	12,13N,10W	St. P.			Top St. P.	4840		1.167	238,000
I O W A												
Cairo	Nat'l. Gas Pipeline		Louisa		St. P.			Perfs.			1.00 est.	1000
Keota	Nat'l. Gas Pipeline		Washington		St. P.			Perfs.			1.00	
Redfield	No. Nat'l. Gas	Hummel No. 1	Dallas	18,79N,28W	St. P.			Top ga.	1741		1.00	1568
Vincent	No. Nat'l. Gas	Peterson No. 1	Webster	10,90N,27W	St. P.	1133	K.B.	Top ga.	1235	-102	1.00	1034
I N D I A N A												
Lake of the Woods, East	No. Ind. Pub. Serv.	H. Ames No. 1 (LWE-88)	Marshall	21,34N,3E	St. P.	789	G.L.	Top ga.	1731	-942	salty	~16,900 (ppm Cl)
								Bottom ga.	1754	-965		
Lakeside	No. Ind. Pub. Serv.	G. Good No. L-1-1	Pulaski	26,29N,3W	St. P. & Knox	686	G.L.				1.008	

*NIG Std. — Northern Illinois Gas Standard (=5.5 feet above casing flange); D.F. — derrick floor; K.B. — kelly bushing; G.L. — ground level.
**The value underlined is considered to be the most reliable value.

ILLINOIS BASIN AND SURROUNDING AREA: ST. PETER

Water-level measurements			Reservoir pressure, from pressure bomb (psig)	Drill-stem tests								$H^{1.00}$**				Remarks
Observed water level, S.L. (ft)	Length of observed water column ($L_{obs.}$)	Length of equiv. fresh-water column ($\rho \times L_{obs.}$)		ICIP (psig)		FCIP (psig)		Pressure at $0 \rightarrow \infty$ (psig)		Equiv. ft fresh water (2.31 x psig)		From water-level observation	From reservoir pressure	From drill-stem test		
				Top ga.	Bottom ga.	Top ga.	Bottom ga.	Top ga.	Bottom ga.	Ft	Derived from			Top ga.	Bottom ga.	
499	211	211										499				
						1650				3812	FCIP			677		
						1584				3659	FCIP			524		
505 est.	1074	1074	475 at -600'							1097	Reserv. press.	505	497			Reported reservoir pressure assumed to be psia
				3388		3388		3453		7976	Extrap. press. Top gauge			761		
					3393		3393			7838	FCIP				603	
						2900				6699	FCIP			-250		Poor DST
514	2057	2068										525				
506	2164	2175										517				
473	4400	4413				2450 (?)				5659	FCIP	486 (DST fill-up)				Poor DST. $H^{1.00}$ is at least 486, probably higher
537	1322	1326	590							1363	Reserv. press.	541	578			Reported reservoir pressure assumed to be psia
735	62	62										735				
				364		367				848	FCIP			536		Ave. $H^{1.00}$ = 534
					366		372			859	FCIP				531	
511			376.7 (depth ?)									511				
			1885			2250				5198	FCIP			556		
						2200				5082	FCIP			469		FCIP could be as low as 2150
561	1925 (DST recovery)	1925				824				1903	FCIP	561 (DST recovery)		539		
							827			1910	FCIP				534	Ave. $H^{1.00}$ = 537
417	2750 (DST recovery)			1226		1230				2841	FCIP	417 (DST recovery)		508		Ave. $H^{1.00}$ = 506
					1265		1266			2924	FCIP				504	
271	4950 (DST recovery)	5297		2256		2279		2285		5278	Extrap. press.	618 (DST recovery)		599		
					2267		2289		2302	5318	Extrap. press.				597	Ave. $H^{1.00}$ = 598
512	771	771										512				
				437		436				1009	ICIP			512		
470	1278	1296										488				
483	1306	1311										489				
475	1421	1438										492				
469	1324	1343										488				
627												627				Measurement made in 1898
																High calcium content
558												558				
610												610				
						700				1617	FCIP					
				465		465				1074	FCIP			972		
508	1450 (DST recovery)			623		625				1444	FCIP			502		
					633		635			1467	FCIP				502	

TABLE 4 - TOTAL DISSOLVED SOLIDS IN SOME ILLINOIS BRINES (FROM MEENTS ET AL., 1952, TABLE 1), WITH CALCULATED VALUES OF ρ AND Z

Reference no.	Well name	Location		Stratigraphic unit	Elevation		Depth to observation pt.	Z	Produced water	
		County	Sec.-T.-R.		Feet	Ref. pt.*			TDS	ρ†
1	Ohio Oil Co., No. 1 Schwartz	Adams	11-2S-6W	St. Peter	646	L & S	344-971	+302	8,210	1.005
2	Ohio Oil Co., No. 1 Fingerlin	Adams	26-2S-8W	St. Peter	566		666-675	-100	12,258	1.008
3	Joe Kesl et al., No. 1 Saathoff	Bond	12-6N-5W	St. Peter	590	P. T.	2,505-3,154	-1,915	12,201	1.008
4	H. R. Snaverly, No. 1 Schofield	Clark	6-11N-11W	St. Peter	526	Topo. map	3,945-3,960	-3,419	124,550	1.088
5	Assoc. Prod. & Tidewater Oil Co., No. 34 Spellbring	Clark	8-11N-14W	St. Peter	659		2,923-3,009	-2,264	24,114	1.016
6	Ohio Oil Co., No. 28-C Ducommon	Crawford	35-6N-13W	St. Peter	477		4,650-4,654	-4,173	160,730	1.108
7	Ohio Oil Co., No. 1 Shaw	Douglas	36-16N-8E	St. Peter	666	G. L.	1,570	-904	24,864	1.017
8	Faulkner, No. 2 Stoneberger	Edgar	3-13N-13W	St. Peter	686	L & S	2,987-2,997	-2,301	48,179	1.032
9	Media Oil Co., No. 1 Pendarvis	Henderson	17-9N-4W	St. Peter	670		934-1,235	-264	1,623	~1.00
10	Gould & Son, No. 1 G. Pearce	Jersey	27-8N-10W	St. Peter	593		1,304-1,802	-711	9,040	1.005
11	Sun Oil Co., No. 1 J. Powers	Macon	30-17N-2E	St. Peter	688	L & S	2,937-2,941	-2,249	6,480	1.004
12	Martin, No. 1 Robinson	Marion	4-2N-1E	St. Peter	523	D. F.	4,270-5,023	-3,747	110,316	1.078
13	Kingwood Oil Co., No. 24A Shanafelt	Marion	20-2N-2E	St. Peter	533	Co.	4,556-5,256	-4,023	127,050	1.09
14	Miss. River Fuel, No. A15 Theobald	Monroe	35-1S-10W	St. Peter	666	D. F.	901	-235	15,714	1.01
15	Forester, No. 1 Forester	Perry	5-6S-1W	St. Peter	465		5,143	-4,678	82,956	1.059
16	Ames Oil Co., No. 1 Nicholson	Randolph	12-5S-9W	St. Peter	615	L & S	1,382-1,840	-767	29,190	1.02
17	Tarlton Oil et al., No. 1-A Dyroff	St. Clair	28-1N-10W	St. Peter	403	Topo. map	890	-487	18,230	1.012
18	Carlson, No. 1 Hedgecook	Schuyler	5-3N-4W	St. Peter	604	L & S	958-975	-354	3,528	1.001
19	Dietrich, No. 2 Mathis	Tazewell	24-25N-3W	St. Peter	785	Topo. map	2,038-2,198	-1,253	1,352	~1.00
20	Panhandle Eastern Pipeline, No. 1-21 Mumford	Pike	21-5S-4W	Shakopee	810	G. L.	914-1,025	-104	4,128	1.002
21	Ohio Oil Co., No. 1 Shaw	Douglas	36-16N-8E	Oneota	666	G. L.	2,150-2,170	-1,484	22,344	1.015
22	Ohio Oil Co., No. 1 Shaw	Douglas	36-16N-8E	Trempealeau	666	G. L.	2,362	-1,696	22,548	1.015
23	Nelson, Erp, & Stroh, No. 1 Erp	Ford	19-24N-7E	Trempealeau	828	Topo. map	2,759-2,985	-1,931	4,098	1.002
24	Ohio Oil Co., No. 1 Shaw	Douglas	36-16N-8E	Franconia	666	G. L.	3,090-3,100	-2,424	26,868	1.018

*L & S - Laughlin & Simmons; P. T. - plane table; Topo. map - estimated from USGS Topographic Map; G. L. - ground level; D. F. - derrick floor; Co. - company records.
†Estimated from figure 9.

TABLE 5 - HEAD AVAILABLE TO CAUSE FLOW FROM MT. SIMON (MT. S.) TO ST. PETER (ST. P.)

Location	$H^{1.00}_{Mt.\ S.}$	$H^{1.00}_{St.\ P.}$	$\rho_{Mt.\ S.}$	$Z_{Mt.\ S.}$	$Z_{St.\ P.}$	$\Delta H^{1.00}-[(\rho_{Mt.S.}-1)\Delta Z]$
Lake of the Woods	618	502	1.10	-2,193	-942	-9
South	629	512	1.004	-1,843	-497	112
Shanghai	631 (Eau Cl.)	512	1.005 (Eau Cl.)	-1,729 (Eau Cl.)	-342	112
Ancona	640	499	1.013	-1,538	+288	117
Crescent City	715	505	1.061	-2,746	-569	133
Mahomet	756	541	1.062	-3,203	-785	65
Lamb	776	525	1.074	-3,834	-1,539	81
Tuscola	756	489	1.082	-3,332	-802	60
Louden	1,028	486	1.145 (Interp.)	-7,453	-3,927	31
St. Jacob	567	506	1.07	-4,451	-2,343	-87
Salem	1,021	598	1.165	-8,367	-4,695	-183
			$\rho_{St.\ P.}$			$\Delta H^{1.00}-[(\rho_{St.P.}-1)\Delta Z]$
Salem			1.075			148

$$\Delta Z_{eq.} = \frac{[\Delta H^{1.00}-(\rho_{St.\ P.}-1)\Delta Z]}{(\rho_{Mt.\ S.} - \rho_{St.\ P.})} = 1{,}640$$

TABLE 6 - HEAD AVAILABLE TO CAUSE FLOW FROM MT. SIMON (MT. S.) TO IRONTON-GALESVILLE (GLSVL.)

Location	$H^{1.00}_{Mt. S.}$	$H^{1.00}_{Glsvl.}$	$\rho_{Mt. S.}$	$Z_{Mt. S.}$	$Z_{Glsvl.}$	$\Delta H^{1.00}$ minus $[(\rho_{Mt. S.}-1)\Delta Z]$
Pecatonica	686 (Eau Cl.)	716	1.00 (Eau Cl.)	+41 (Eau Cl.)	+182	-30
Brookville	648	682	1.00			-34
South	629	513	1.004	-1,843	-1,497	115
Shanghai	631 (Eau Cl.)	513	1.005 (Eau Cl.)	-1,729 (Eau Cl.)	-1,417	116
Troy Grove	645	595	1.00	-738	-227	50
Ancona	640	496	1.011	-1,538	-1,084	139
Herscher	654	480	1.013	-1,761	-1,081	165
Pontiac	673	515	1.034	-2,276	-1,746	140
Crescent City	715	505	1.061	-2,746	-2,000	165
Lake Bloomington	697	513	1.045	-2,881	-2,283	157
Lexington	714	512	1.052	-3,010	-2,414	171
Mahomet	756	536	1.062	-3,203	-2,519	178
Hudson	723	527	1.053	-3,180	-2,492	160
Lake of the Woods	618	529	1.10	-2,193	-1,596	29
Royal Center	539* 585**	498 498	1.065* 1.070**	-2,044 -2,140	-1,336 -1,336	-5 +31

*Top of Mt. Simon.
**Average of 6 values near top of Mt. Simon.

TABLE 7 - HEAD AVAILABLE TO CAUSE FLOW FROM IRONTON-GALESVILLE (GLSVL.) TO ST. PETER (ST. P.)

Location	$H^{1.00}_{Glsvl.}$	$H^{1.00}_{St.\ P.}$	$\Delta H^{1.00}$	$[\Delta H-(\rho_{Glsvl.}-1)\Delta Z]$*
Pecatonica	716	735	-19	-19
Shanghai	513	512	+1	+1
Ancona	496	499	-3	-3
Pontiac	515	511	+4	+4
Crescent City	505	505	0	-56
Mahomet	536	451	+85	+40
South	513	512	+1	-1

*For Crescent City, $\rho_{Glsvl.}$ = 1.039, ΔZ = 1,431.

For Mahomet, $\rho_{Glsvl.}$ = 1.026, ΔZ = 1,734.

For South, $\rho_{Glsvl.}$ = 1.002, ΔZ = 1,000.

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